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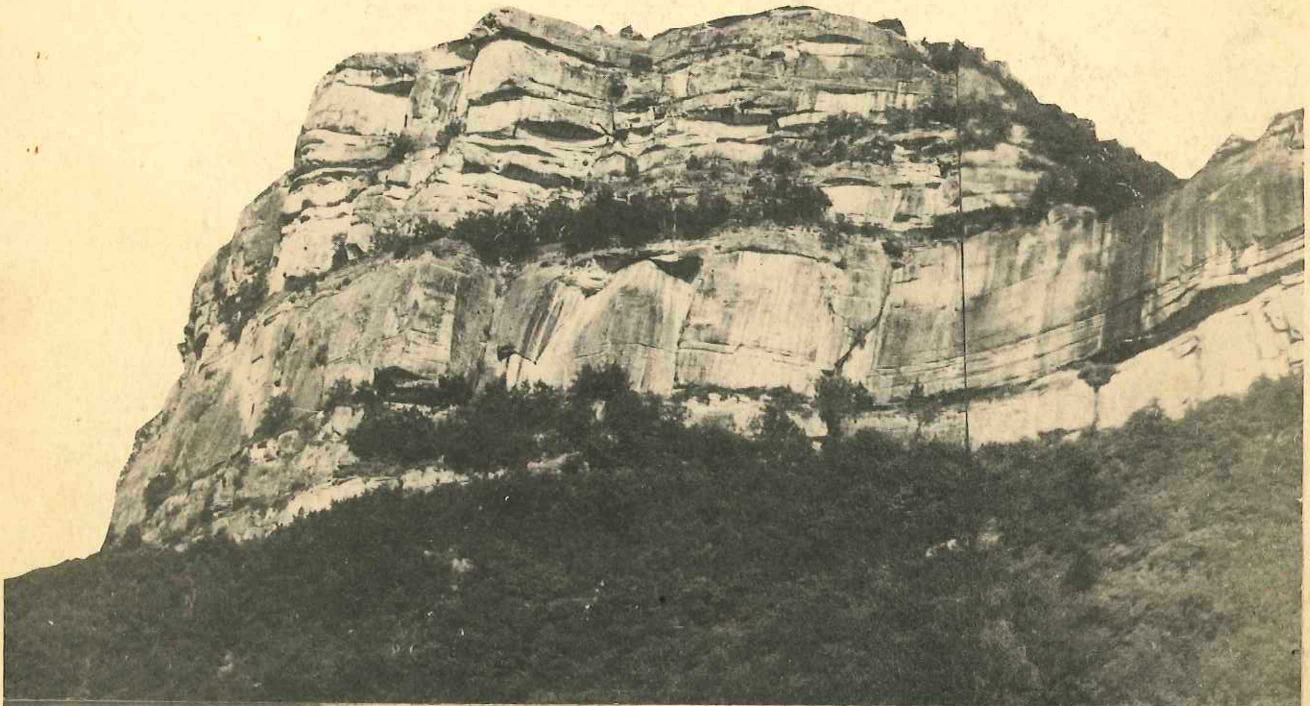

SUBMARINE CANYON AND SLOPE SEDIMENTATION (GRES D'ANNOT) IN THE FRENCH MARITIME ALPS

Cover photographs: upper, shows massive standstone units of the gres d'Annot Formation above Les Scaffarels (Basses-Alpes) interpreted as submarine canyon fill facies; lower, shows underwater sand fall at a depth of 40 m in San Lucas Canyon off Baja California (photo courtesy of R.F. Dill).

SUBMARINE CANYON AND SLOPE SEDIMENTATION (GRES D'ANNOT) IN THE FRENCH MARITIME ALPS

SEDIMENTATION DES PENTES ET CANYONS SOUS-MARINS (GRES D'ANNOT) DANS LES ALPES MARITIMES FRANÇAISES

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S E D I M NICE 75

IXme CONGRÈS INTERNATIONAL
DE SEDIMENTOLOGIE
NICE 1975

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SEDIMENTATION (GRES D'ANNOT) IN THE
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ABSTRACT

The Annot Sandstone Formation, a thick marine sequence of Uppermost Eocene to Lower Oligocene age in the Maritime Alps of France and Italy, presents remarkably well-exposed massive sandstone, pebbly sandstone and pebbly mudstone sequences associated with the more classic alternating sandstone turbidite-shale flysch facies associated with this formation. The purpose of this presentation is to review the salient characteristics of these coarse, shoe-string bodies interpreted as submarine valley deposits, and to examine details of channel (including submarine canyon) fill, submarine valley wall, intervalley slope and submarine fan lithofacies. The interrelation of these facies in space and time is observed, and an interpretation is made of the dominant processes responsible for the transport of sediment from basin margins to deeper environments. A bathyal depth is indicated by ichnofossil assemblages and additional sedimentological evidence.

Formulation of a submarine canyon sedimentation model, based in part on studies in modern canyons, is made using as example the channelized sandflow and related deposits at the Annot, Contes and Menton localities. In contrast, facies observed in the more distal localities to the north (Lac d'Allos, Peïra-Cava and Sospel regions) display fewer and thinner massive units and a higher proportion of turbidites and shales; these sequences are interpreted in terms of the now reasonably well-defined submarine fan sedimentation models. Examples of both inner and more distal outer fan facies are distinguished.

Mapping of the canyon to fan transition provides greater precision to the Annot Basin paleogeographic interpretations. Furthermore, these channel deposits, unusual in the sense that they can be traced so clearly laterally

along paleoslopes afford a rare opportunity to observe the downslope transformation of subaqueous flow mechanisms (i.e., slump, debris flow and diverse sand flow processes including grain/fluidized and turbidity currents). The massive sandstone units of Annot Sandstone examined here are designated as a type example of the submarine canyon-fan valley continuum.

RESUME

Les grès d'Annot dans les Alpes maritimes françaises et italiennes forment une séquence marine épaisse dont l'âge est compris entre l'Eocène supérieur et l'Oligocène inférieur. On y trouve, en plus des faciès de flysch (alternance de turbidites et de schistes) caractéristiques de cette formation, des séries particulièrement bien exposées de banc de grès massifs, de grès à galets et des masses argilo-gréseuses à conglomérats.

On énumèrera les traits marquants de ces matériaux grossiers qu'on peut considérer comme des remplissages de vallées sous-marines et on étudira les détails de ces chenaux (canyon sous-marin inclu), parois de canyons, faciès de pentes et de cônes à la base de la pente. On observera la corrélation de ces faciès dans le temps et dans l'espace et on interprètera les processus dominants responsables du transport du sédiment des marges vers des zones plus profondes (bathyales) du bassin; les associations d'ichnofossiles et d'autres données sédimentologiques fournissent les informations sur la paléobathymetrie.

On peut élaborer un modèle de sédimentation dans un canyon sous-marin en utilisant les études sur les canyons modernes et en se servant de l'exemple des dépôts canalisés et des séquences associées dans les régions d'Annot, de Contes et de Menton. Les faciès au Nord de ces régions (Lac d'Allos, Peïra Cava et Sospel) présentent une plus haute incidence de turbidites qu'on peut interpréter, grâce aux modèles de sédimentation, comme des cônes s'accumulant à la base des pentes sous-marines. On observera les divers faciès dans les zones internes et externes de ces cônes.

L'identification de la transition du facies canyon au faciès chenal de cône nous permet de mieux préciser la configuration paléogéographique du Bassin d'Annot. Ces chenaux dans les grès d'Annot, si admirablement bien préservés qu'on peut les suivre en trois dimensions sur des étendues considérables, permettent de suivre le long de la pente les phases successives de transition des mécanismes de transport (mouvement en masse, coulée sableuse fluide et courant de turbidité). Ces dépôts sableux peuvent être cités comme exemple typique du complexe canyon sous-marin - chenal de cône.

CONTENTS

If things in nature are beautiful, their beauty is not superficial but the resultant form of definite purpose.

Andreas Feininger, 1956
The Anatomy of Nature.

INTRODUCTION

Sea floor investigations in the different world oceans have demonstrated that modern continental margins and basins are almost everywhere dissected by valleys, some of them spectacular in size and shape. These features were recognized in early marine surveys (Dana, 1863, and others), and in recent years considerable advances have been made in defining the physiography and sediments of submarine canyons and interpreting the physical and biological processes active in them. For a comprehensive treatment of this subject, the reader is directed to the recent reviews by Shepard and Dill (1966) and Heezen and Hollister (1971).

The development of seismic surveying has provided a means to evaluate the three dimensional configuration of submarine canyon deposits in modern oceans. This and visual observations by SCUBA, submersible diving, underwater camera and television, supplemented by physical oceanographic systems such as current meters, have considerably increased our understanding of the processes responsible for the movement of sediment in these generally narrow, elongate downslope-trending depressions. There is little doubt that submarine canyons, gullies, troughs and related features, mapped in all of the world oceans, have played an important role in the transfer of sediment from terrestrial and shelf platform areas to the deep sea. As demonstrated by the pioneer work of Francis P. Shepard, and subsequently substantiated by many others, submarine valleys serve as funnels through which coarse, as well as fine, materials bypass neritic environments and move relatively rapidly downslope.

Although the amount of literature on the subject of canyons has grown rapidly and oceanographic techniques have considerably evolved during the past

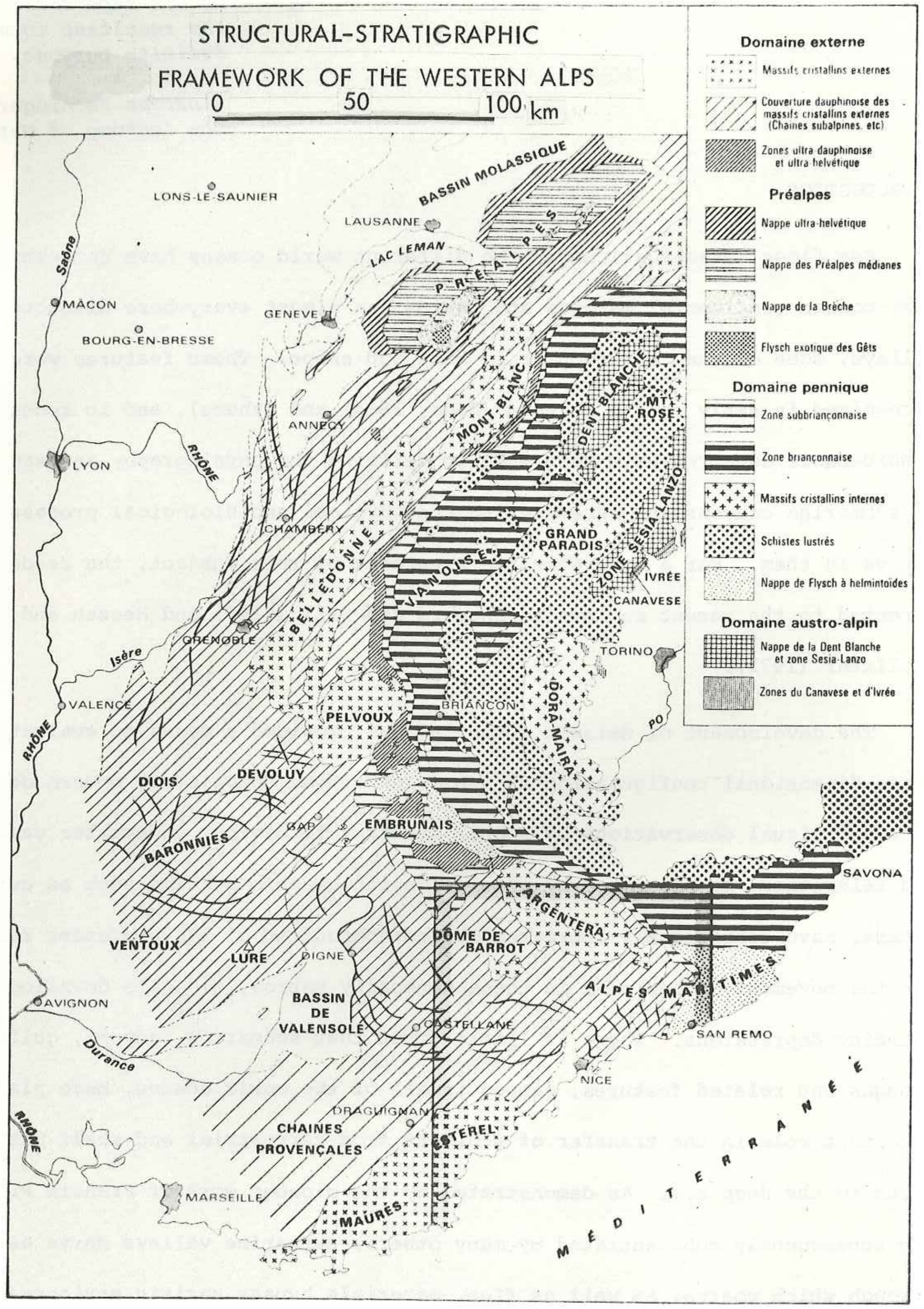


Fig. 1. Map showing the structural-stratigraphic framework of the western Alps and study area (after Bodelle et al., 1968).

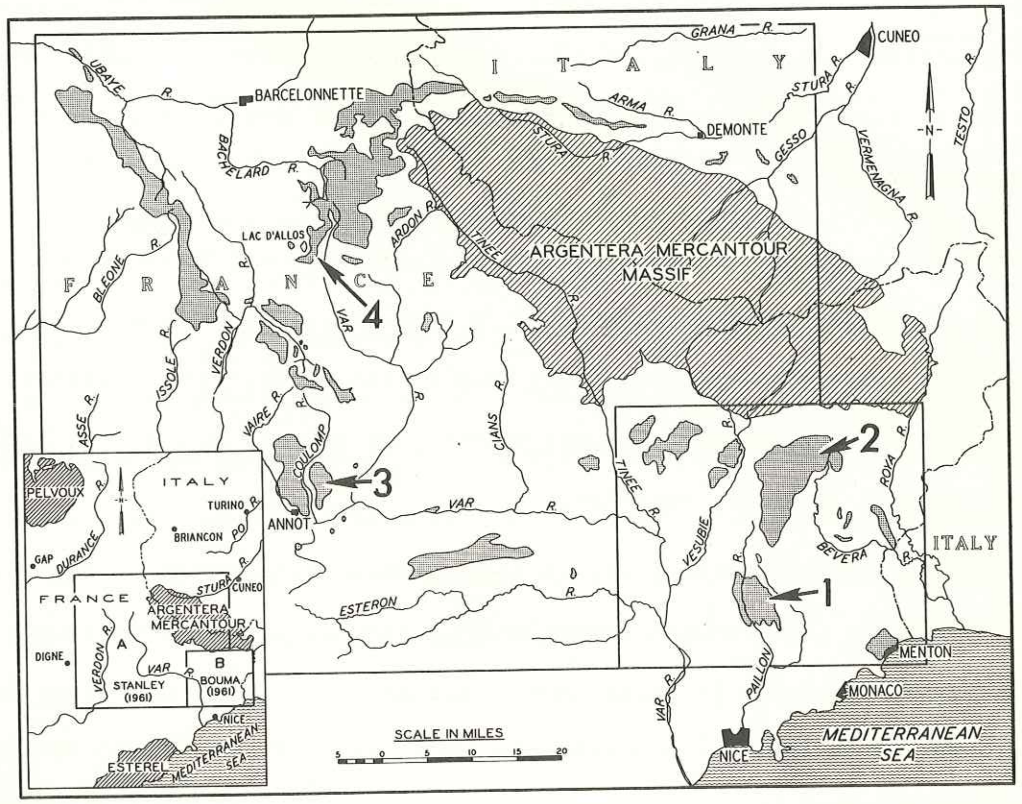


Fig. 2. Annot Sandstone *s.l.* outcrop localities (stippled pattern) in the Maritime Alps. The numbers refer to the four areas examined in this study (details *in* Appendix; see also Figs. 61 and 62).

few years, a number of difficulties remain. These are related to the acoustic limitations of standard broad beam echo-sounders and seismic subbottom systems used in narrow, steeply dipping submarine environments, the small penetration of canyon sediment by piston cores, and the relatively low recovery rate of long-term bottom monitoring systems such as current meters. As a result, studies of modern canyons have not provided a really thorough definition of the depositional origin of sedimentary bodies and their three-dimensional configuration within these linear depressions. For this reason it is most valuable to seek out and examine at close hand examples of submarine canyon deposits preserved in the geological record.

Little was known of such facies until recently. Recent focus on ancient canyon and fan valley deposits (summaries *in* Sullwold, 1960; Walker, 1966; Stanley, 1967, 1969; Ricci Lucchi, 1969; Stanley and Unrug, 1972; Whitaker, 1974) indicates that such units, although not common, are present in every geological system as far back as the Precambrian.

Among the best exposures of lithologic sequences interpreted as submarine canyon deposits are those of the grès d'Annot Formation of uppermost Eocene to lower Oligocene age in the Maritime Alps. This marine formation consists largely of sandstones and shales, and presents throughout much of its outcrop area most of the characteristics attributed to classic flysch (i.e., distinct alternation of well-stratified sandstones, turbidites and shales; typical sole markings and other sedimentary structures; paleocurrent directions that are generally consistent at any one outcrop locality; trace fossil assemblages indicative of outer neritic to bathyal depths; etc.). Considerable attention has been paid to these flysch attributes of the Annot Sandstone (cf., Stanley, 1961; Bouma, 1962; Lanteaume et al., 1967).

This guide has a more specific purpose: to focus on thick, moderate- to coarse-textured shoe-string shaped sandstone and pebbly sandstone bodies within the Annot Formation. This type of massive channelized sandstone facies, if not actually ignored, until recently has been considered anomalous and rather atypical

of flysch formations (Dzulynski et al., 1959). The salient characteristics of these linear sandstone units associated with more typical flysch are reviewed, and particular attention is paid to (1) details of the prevalent lithofacies, (2) the interrelation of such facies in space and time and (3) the transport processes responsible for their accumulation.

The importance of mapping such facies in ancient marine formations should be readily apparent. Submarine valley deposits provide an excellent means of reconstructing the configuration of ancient marine basins, particularly paleoslopes, and enable the geologist to define the dispersal paths between shallow marine and more distal basinal environments. Examination of fossil canyon units provides an insight — admittedly indirect — of the transport processes, an aspect that does not readily lend itself to study by the geological oceanographer; this type of information, frozen as it were in the rock record, can assist the marine geologist in his interpretation of modern slope sedimentation. Furthermore, the practical application of such studies in subsurface and offshore oil exploration is not a negligible one: it already has been demonstrated that fossil submarine valleys deposits are in some instances ideal sandstone traps and thus extremely attractive targets of commercial consequence.

GENERAL GEOLOGICAL BACKGROUND

The study area occupies a sector of the external Alpine chain (Ultra-dauphinois and Dauphinois structural-stratigraphic zones) between three Hercynian crystalline massifs: the Pelvoux Massif to the north, the Argentera-Mercantour Massif to the east and the Esterel Massif to the south (Fig. 1). Among the oldest sedimentary formations in this region are the clastic units of Permian and Werfenian (Lower Triassic) age which form the Dôme de Barrot and also crop out along the southeastern margin of the Argentera-Mercantour Massif. The post-Werfenian to pre-Oligocene formations in the region between the massifs of the Maritime Alps account for at least 2000 m of section. These Mesozoic to early Tertiary sequences are almost completely sandstone-free; above the Middle Triassic evaporites lie diverse formations of limestone, dolomite and shale.

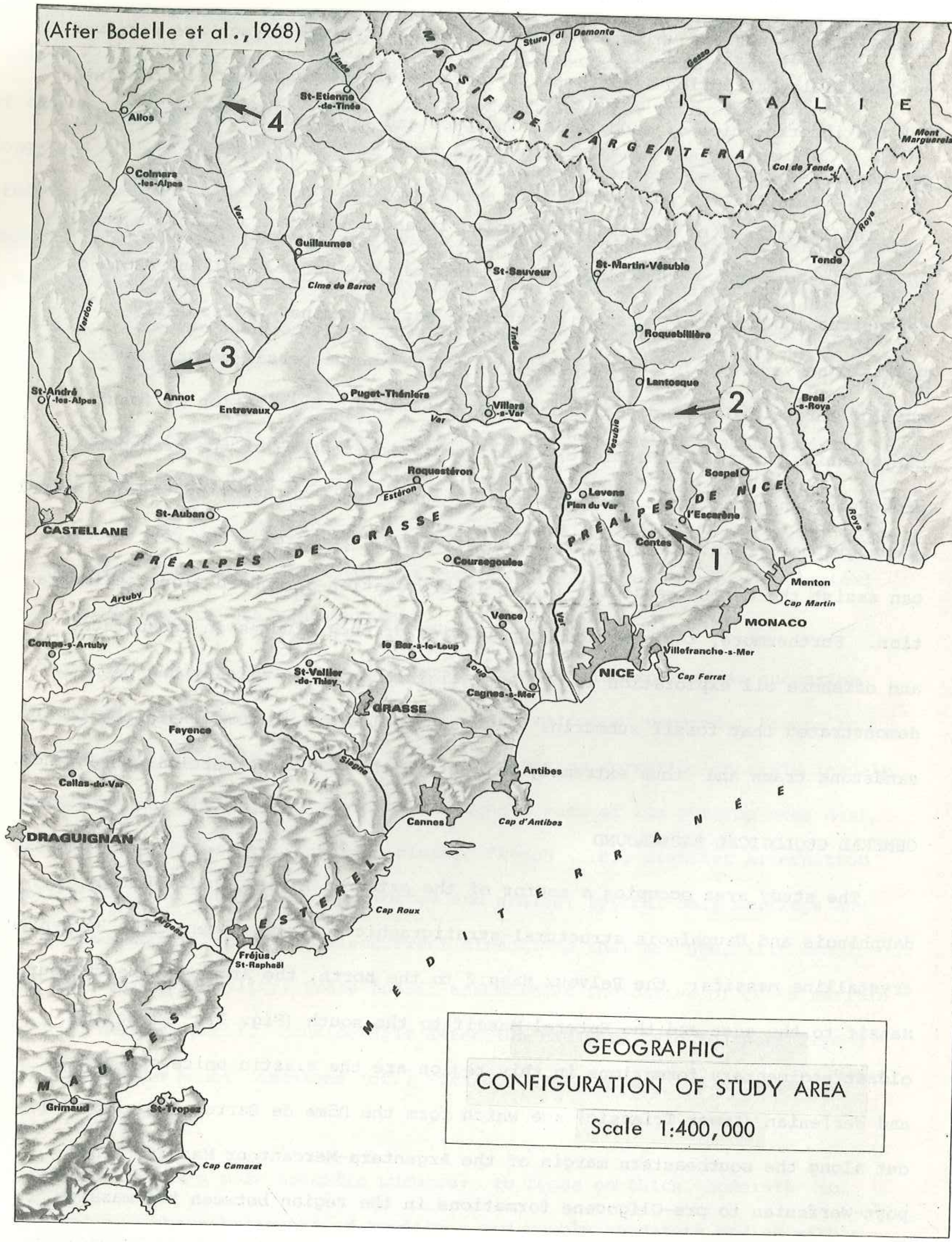


Fig. 3. Map showing the geographic configuration of the French and Italian Maritime Alps and the four localities examined in this study (after Bodelle et al., 1968).

A marked unconformable surface separates the Upper Cretaceous marine limestone formations from the overlying Tertiary sequences, commonly referred to as the *formations nummulitiques*. These overlying marine units consist essentially of three lithofacies: limestone (Conglomérat à *microcodium* and *Calcaire nummulitique*), shale (*Marnes bleues*, or, if well indurated, *calcschistes à globigérines*) of Priabonian age, and the uppermost sandstone and shale formation (*grès d'Annot*) dated as uppermost Eocene to lower Oligocene. This sequence represents the *trilogie priabonienne* of Moret (1954) and others, and the biostratigraphy of the limestones, marls and shales underlying the sandstones of this region have been detailed by Bodelle (1971). The Annot Sandstone and lateral equivalent clastic units to the south, at Saint Antonin, and in the region to the west (Barrême, Clumanc, etc.) are the youngest marine sequences deposited in this region.

Nummulitique sequences, noticeably reduced in thickness toward the west (external zone), were covered by a younger series of littoral, lacustrian and continental origin (*Molasse rouge*). The Mesozoic and Tertiary units of the Ubaye-Embrunais and Helminthoïdes nappes cover the authochthonous and para-autochthonous series, including the Annot Sandstone, in the sector west and northwest of the Argentera-Mercantour Massif.

Exposures of the Annot Sandstone Formation lie within an area of approximately 8000 km^2 in the Basses Alpes and Alpes Maritimes departments of France and the Stura Valley west of Cuneo in Italy (Figs. 2 and 3). Gras (1840), one of the early geologists working in this region, noted the similarities of Nummulitique formations in the different localities and depicted the feldspathic, micaceous sandstones as a regionally mappable unit. Subsequent geologists attributed different geographic names to the sandstone-rich sequences at each outcrop locality (grès d'Annot, grès de Peïra-Cava, grès de Contes, etc.). Regional sedimentological and stratigraphic analyses show that the sandstone and shale sequences throughout the region are genetically related (Stanley, 1961; Bouma, 1962), and I term the formation the Annot Sandstone *sensu lato*. It must be recognized that the lithofacies vary considerably in time and space, and that the basal Annot Sandstone strata in the different synclines probably are not strictly synchronous although biostratigraphic analyses of the upper fossiliferous Marnes bleues (= calcschistes) underlying them indicate an upper Eocene age in most localities.

As the Alpine chain evolved during the early Tertiary the marine transgression progressed westwardly over a subsiding sea floor. The faunal composition of the Calcaire nummulitique and Marnes bleues shows a progressive deepening of the peri-Alpine Sea over this region during the Eocene. The shales preceding the Annot Sandstone are attributed a neritic origin based, in part, on faunal assemblages (Fig. 4; Bodelle, 1971).

The sea floor on which the sandstones began to accumulate became physiographically more complex as a result of important end-of-Eocene tectonic phases, and some large-scale structural offset occurred during deposition of the grès d'Annot (Gubler, 1958). Increasingly important tectonic movements occurred at different times during the Oligocene, resulting in the emplacement of nappes in the region west of the Argentera-Mercantour Massif (Fig. 1). The major structural configuration of the region, including development of the tectonostratigraphic configuration of the Castellane and Nice "arcs", is attributed to Miocene structural phases, and the intensity of these movements reached a maximum in Pontian time. The broad regional change in configuration of land versus sea initiated in the Miocene became even more pronounced in the Pliocene as emersion and uplift of the Alps continued and land masses to the south of the present Mediterranean coast subsided and foundered. As a result of this alteration in regional tilt (*flexure continentale* of Bourcart, 1959), rivers which had once flowed northward reversed and transported sediments to the south. Directly associated with this evolution on land is the opening and marked deepening of the Ligurian Sea lying between Corsica and the Riviera (Fig. 5; cf., Auzende et al., 1973).

Terrains north and northwest of Nice traversed during the excursion (see Appendix for details) are depicted on the following geological maps (Carte

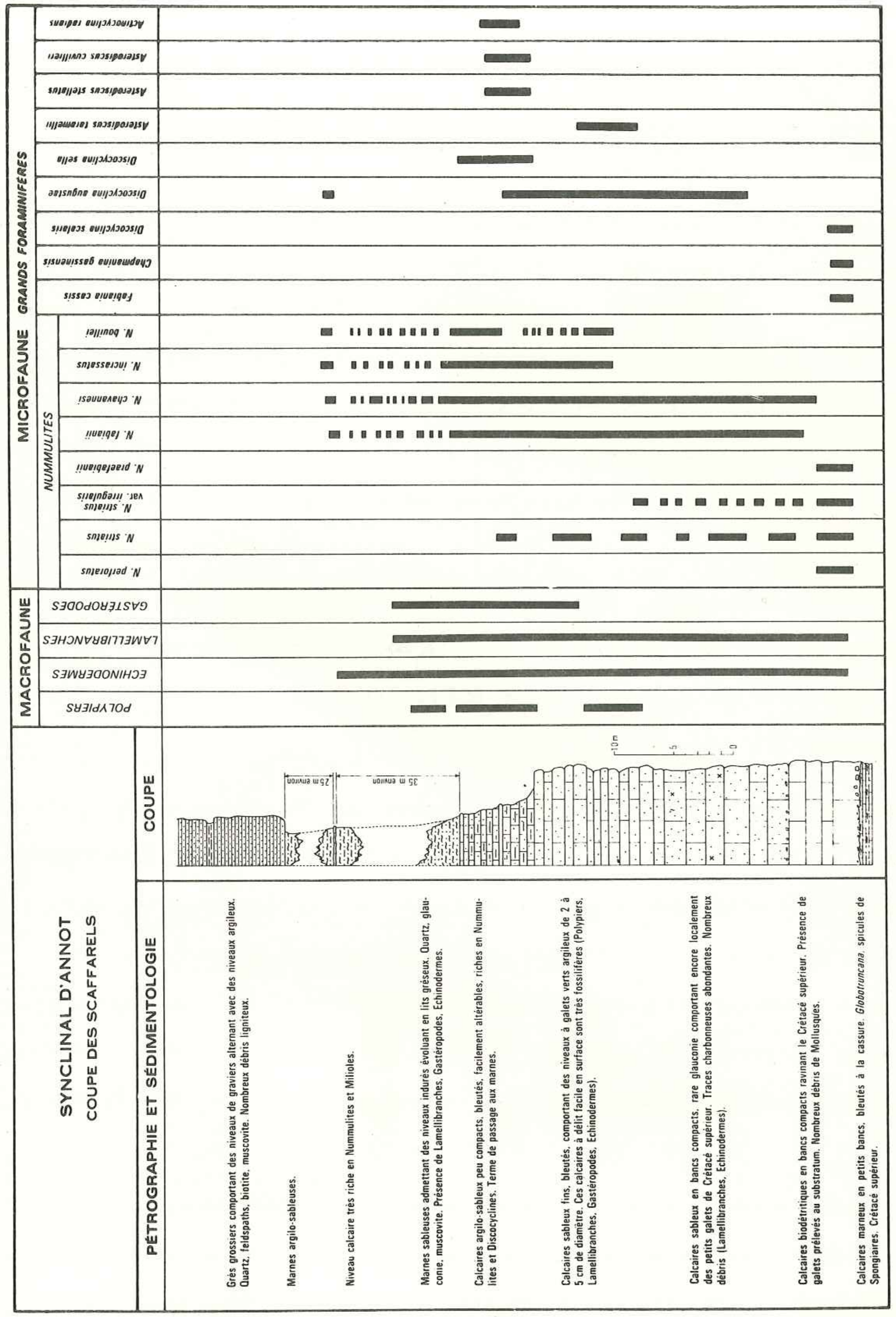


Fig. 4. Faunal composition and petrology of the Eocene limestone (*Calcaire nummulitique*) and shales (*Marnes bleues*) at the base of the Annot Sandstone at its type locality near Annot (after Bodelle et al., 1968).

Géologique de la France, Bureau de Recherches Géologiques et Minières): *Nice, St. Martin-Vésubie, Digne*, at a scale of 1:80,000; *Menton-Nice, St. Martin-Vésubie, Pugét-Théniers, St. Etienne-de-Tinée, Allos*, at a scale of 1:50,000.

Several useful geological guides describing the general structural configuration and stratigraphic sequences of this region include those by de Lapparent (1938), Goguel (1953), Bodelle et al. (1968), Glintzboeckel and Horon (1973) and Debelmas (1970, 1974).

CONFIGURATION OF THE ANNOT BASIN

A series of regional sedimentological analyses have been made of the various Annot Sandstone localities (grès d'Annot, grès de Contes, grès de Peïra-Cava, grès de Menton, etc. termed the Annot Formation *s.l.*) and their lithologically different lateral equivalents (gres de Saint Antonin, Clumanc, Senez, etc.) (Stanley, 1961, 1965; Bouma, 1962; Stanley and Bouma, 1964). These studies have defined the general configuration of the late Eocene-early Oligocene sea; this marine realm which occupied what is now the Maritime Alps is termed the Annot Basin (Stanley and Unrug, 1972).

Field work has emphasized details of strata type and sequence, sedimentary structures, trace fossil assemblages (Wexler, in preparation) and paleocurrent analysis, all of which have served to define the basin paleomorphology including slope, base-of-slope (apron, fan) and basin environments, and the dispersal patterns in the different parts of the basin. These studies are complemented by textural analyses which shed light on transport mechanisms, and by mineralogical investigations which assist in the determination of the sand and gravel source areas.

Schematic diagrams in Figure 5 serve to highlight the reconstructed paleogeography of the Annot Basin toward the end of Eocene time (after Stanley, 1961; Stanley and Bouma, 1964). In diagram 1, paleoslopes (represented by hachures) are shown dipping north, east and west into a basin whose depth is estimated at 1000 m and perhaps more. The basin lay west of the Argentera-Mercantour Massif (a) and Dôme de Barrot (b), and north of the Maures-Esterel

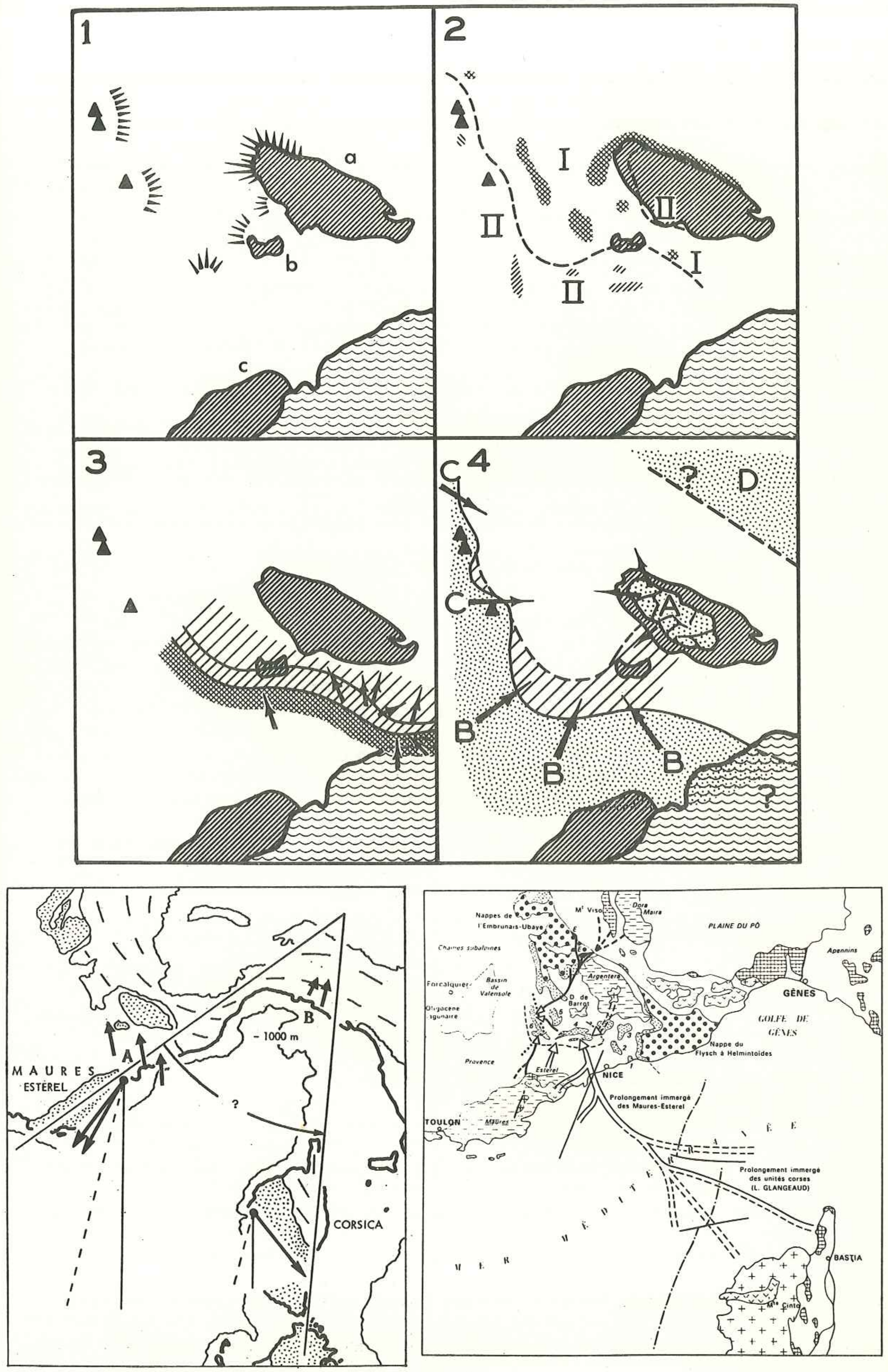


Fig. 5. Upper, paleogeographic reconstruction of the Annot Basin (after Stanley, 1961; Stanley and Bouma, 1964). Details in text. Lower left and right, interpretations depicting a southern (Mediterranean) source area which provided sediment to the Annot Sandstones *s.l.* (after Stanley and Mutti, 1968; and Bodelle, 1971).

Massif (c). The position of the slopes delineates the irregular shape of the furrow in which were deposited thick (500-600 m) sequences of well-stratified sands and muds. The Annot Basin does not display a simple elongate trough configuration of the type frequently depicted for flysch seas. The sea floor was probably topographically complex and almost certainly included depressions separated by ridges as in the case of modern basins in the Mediterranean (cf., isolated basins in the Aegean area) or the region off southern California. Large gravity slump blocks and conglomerates are locally important and where concentrated depict the position of base-of-slope environments (Gorsline and Emery, 1959). Minimum paleoslope gradients of at least 3° are postulated for movement of large blocks (cf., Moore, 1961 and others); slopes almost certainly exceeded 5° locally, as in the case of most ocean margins.

Diagram 2 subdivides the Annot formation *s.l.* into two zones: one comprising the more typical flysch facies (I) of this unit which accumulated on slope, fan and deeper environments, and a zone of non-flysch (II) facies (including sands and conglomerates at Saint Antonin, Fig. 8, calcareous sands in the Castellane-Clumanc sector, etc.) deposited on the shallower, probably narrow margins of the basin. This deep basin-narrow shelf configuration is typical of most modern basins in tectonic settings (eastern Mediterranean, circum-Pacific, Caribbean, etc.).

In diagram 3, the arrows indicate predominant paleocurrent directions measured in the southern sector of the Annot Basin, the region discussed in this study and detailed in Stanley (1961) and Bouma (1962). Sediments were transported northward away from the Maures-Esterel Massif and from what is now deep ocean in the present Mediterranean area (Kuenen, 1959; Stanley and Mutti, 1968; Bodelle, 1971). This conclusion is based on the geometry of sandstone and conglomerate bodies, sedimentary structures indicating paleocurrent directions to the north, and composition of pebbles having an Esterel/Corsica affinity. The east-west hachured bands, becoming progressively lighter toward the north, symbolize a thinning and fining of turbidites and other sand units toward the

north. The slope appears to be at least 10 km wide, or comparable, for example, to margins bounding modern basins in both the eastern and western Mediterranean.

In diagram 4 are depicted the four major source areas (A, B, C, D) believed to have shed material into the Annot Basin. Note that although the well-exposed crystalline rocks of the Argentera Massif (A) are adjacent to the outcrop localities, only a small (northwest) sector of this zone served as a source at the end of Eocene time. It has been suggested that erosion of Permian-Triassic clastics furnished much material to the Annot Basin in the northern sector (Gubler, 1958; Stanley, 1965). Area B, lying to the south (most likely part of the once-subaerially exposed Esterel-Tyrrhenide land mass in Liguria between the Riviera and Corsica which became submerged in the Oligocene and foundered in post-Oligocene time) was a major source as indicated not only by paleocurrents but also by the abundance of red granite, andesite and rhyolite pebbles (Fig. 6) and the suite of heavy minerals that includes staurolite and kyanite not found in the Argentera-Mercantour Massif (Fig. 7). Sediments derived from sources A and B were carried into the basin and mixed in the sector delineated by hachures.

One of the southern upland source areas lay in the area south of Saint Antonin where a coarsening-upward vertical sequence of shales to poorly consolidated sandstones and conglomerates (Fig. 8), including volcanic elements, records a shallow marine to fluvio-deltaic evolution. The feldspathic, lithic sandstones are partly equivalent in age to the Annot Sandstone exposures to the north and northwest while the polymictic conglomerate series may be somewhat younger. The biostratigraphic and petrologic characters of the Saint Antonin sections recently have been described in detail by Bodelle (1971). It is possible that one of the major delta point sources which fed coarse sediment northward to the Annot Basin occupied this region.

Having provided a simplified paleogeographic framework for this tectonically active late Eocene to early Oligocene marine basin, we will now focus on several

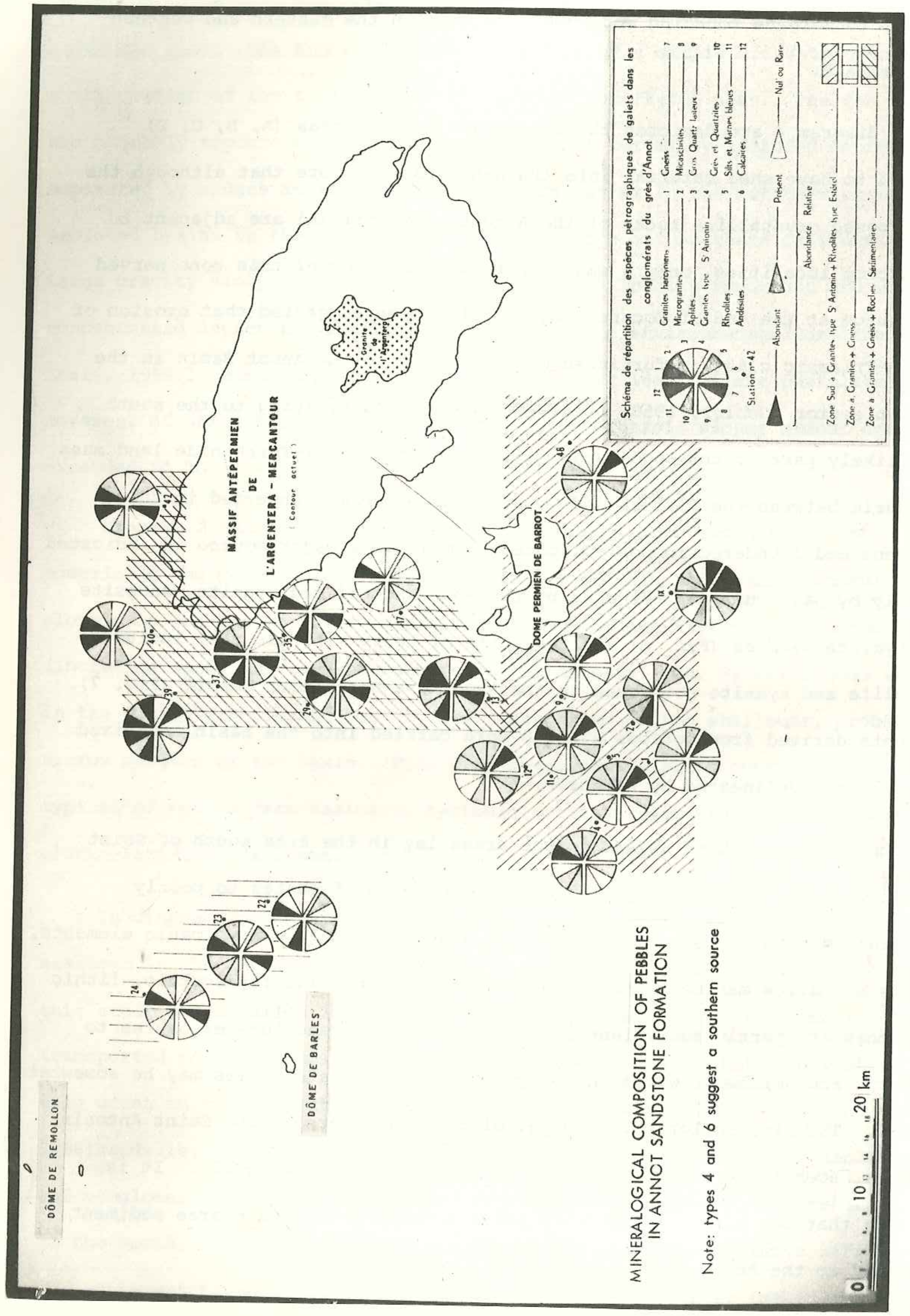
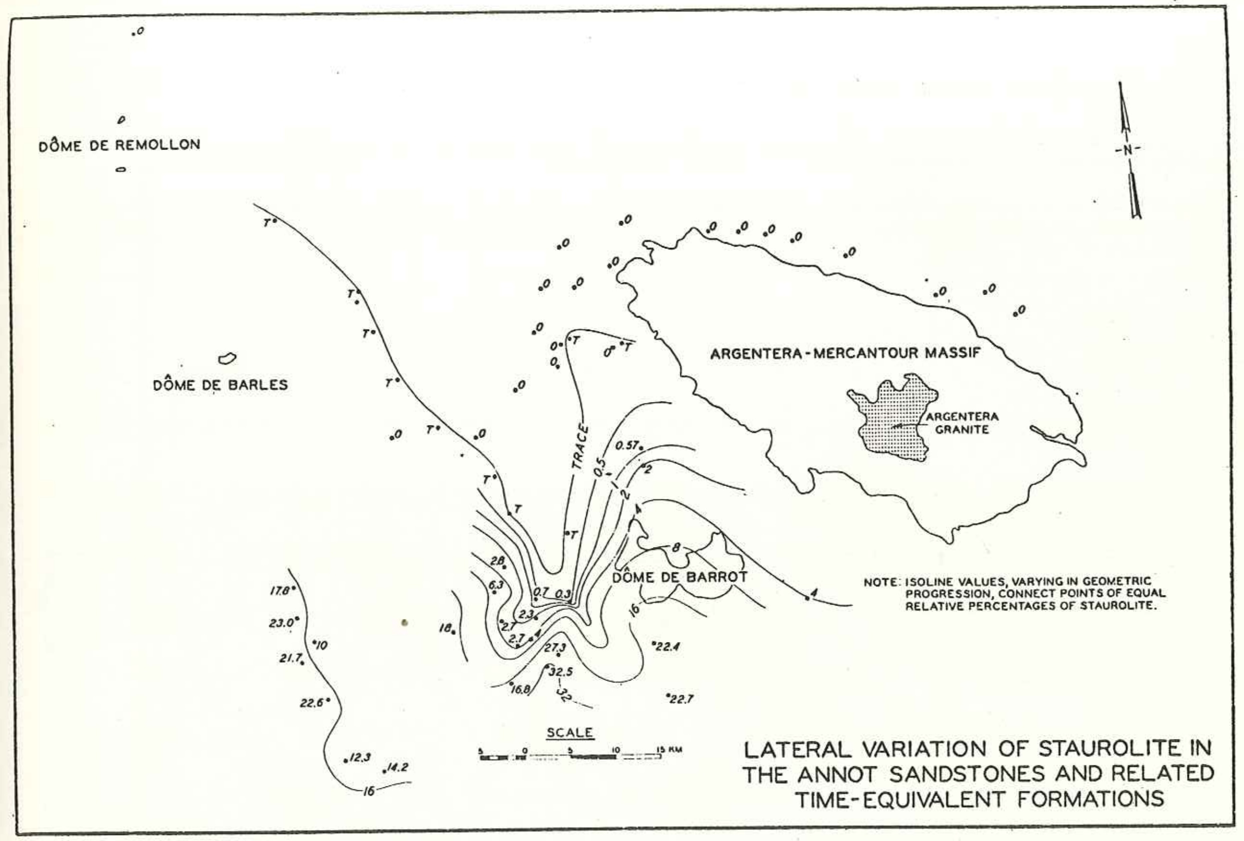


Fig. 6. Mineralogical composition of pebbles in the Annot Sandstone localities; assemblages indicate provenance from three different major source areas (after Stanley, 1961).



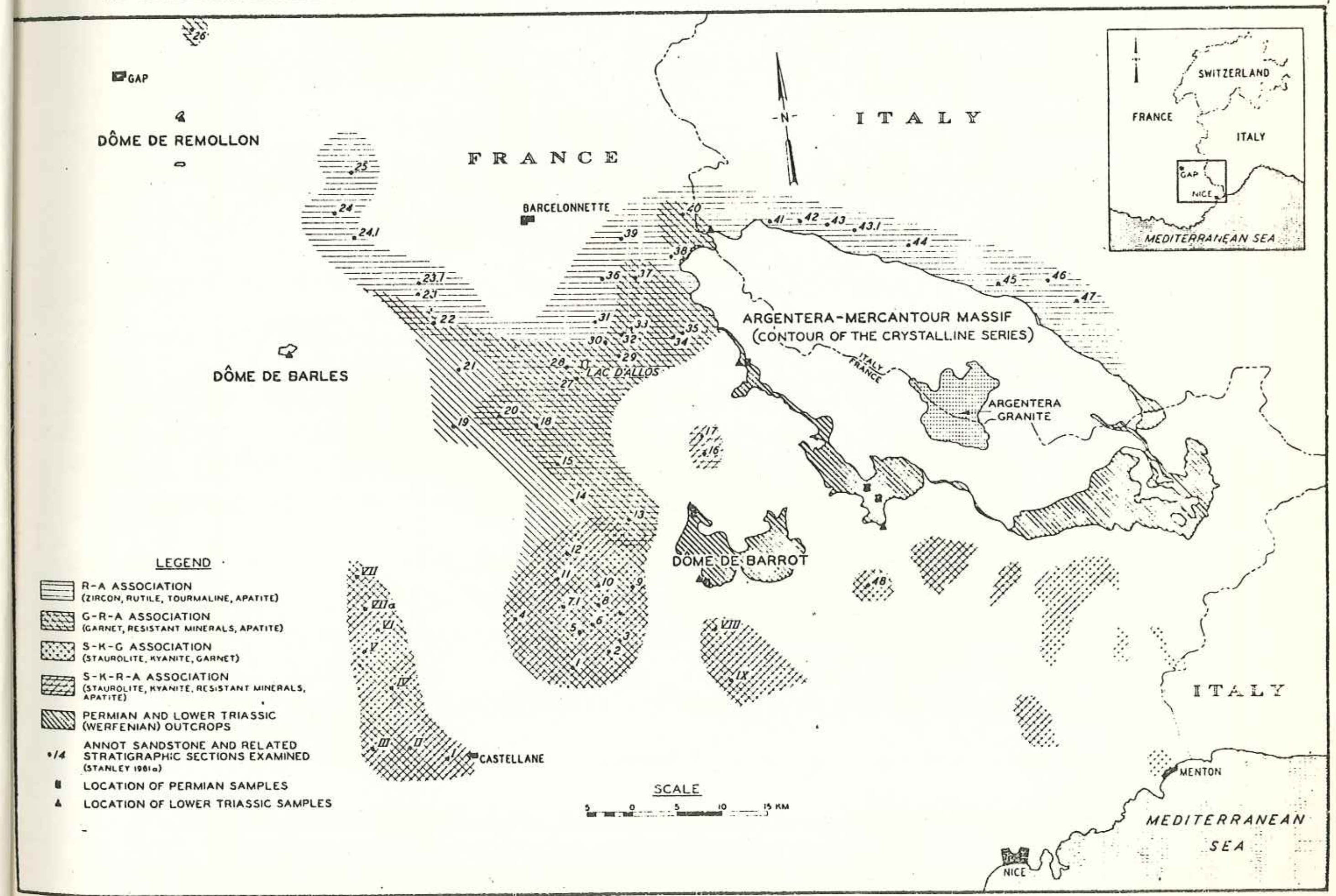


Fig. 7. Upper, map shows decrease of staurolite toward the north; this mineral is attributed a southern origin. Lower, Annot Sandstone heavy mineral assemblages showing the influence of both southern (Mediterranean) and Mercantour sources (after Stanley, 1961).

localities where slope deposits are well exposed. Particular attention will be paid to those areas recording evidence of submarine valleys which served as byways for downslope movement of the coarse sediment northward into the Annot Basin.

ANNOT BASIN PALEOSLOPE SECTORS SELECTED FOR STUDY

Areas Examined

Several localities of the Annot Formation which present excellent examples of slope deposits, including possible submarine valley facies, are easily accessible from Nice. Several of these localities include lithofacies which are not typical of flysch (i.e., in classic terms, the thick, marine, well-stratified alternating sandstone turbidite-shale sequences) and which have been interpreted by some workers as shallow marine deposits (Boussac, 1912; Iwuchukwu, 1968) because of the predominance of thick coarse-textured sandstone strata, pebbles, and plant matter and the poor faunal content in these sections. Four outcrop localities are noteworthy in this respect and include, from west to east, Annot, Contes, Menton and Mortola (Fig. 9-13). The Annot Formation, the youngest marine member above Eocene limestones and shales, crops out within asymmetrically deformed synclines in these regions. Sandstone strata are generally well-exposed and present relatively low (by Alpine standard) structural dips (generally <30°). It should be noted that the Annot Formation in synclines north of these four regions display the flysch aspect more generally considered typical of this formation. A suggested itinerary and logistical guide provided in the Appendix will assist the reader interested in visiting the localities cited in this study.

Annot Region

The sandstone cliffs which dominate the medieval village of Annot in the Basses-Alpes have long been a source of wonderment to tourists and geologists alike. The N-S trending sequences covering about 20 km^2 along the Vaïre and Coulomp rivers present the best and least deformed exposures of the four regions cited above. It is from this locality that the formation derives its name

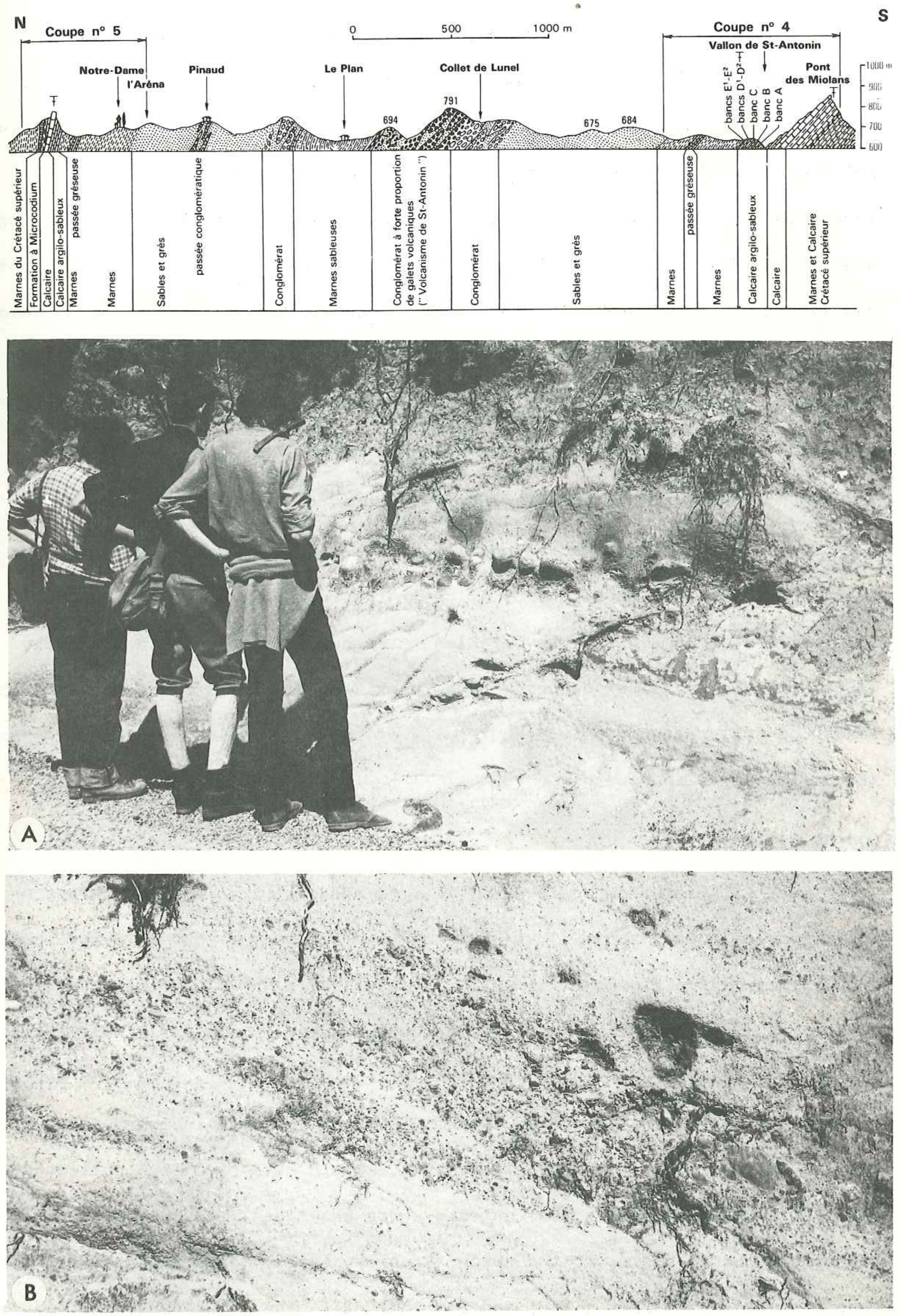


Fig. 8. Stratigraphic section across the St. Antonin syncline showing coarse clastic sequences (after Bodelle et al., 1968); A, B, exposures of friable sandstones and conglomerates (shallow marine to deltaic sequences) near St. Antonin.

(Figs. 9, 22). This region includes a 250 to 300 m thick section of friable Annot Sandstone above the Calcaire nummulitique and Marnes bleues sections, including: (1) very thick shoe-string sandstone beds west of the Coulomp River which can be followed between the Chambre du Roi and Gros Vallon de Fugeret localities northward to le Ruch; (2) poor exposures of friable sands at Allons west of the Vaïre River and at Rouaine, Ourges and Courleveras south of Annot; and (3) flysch-type facies forming the Crête de la Barre, Gros Vallon de Saint Benoit, Col du Fa and Castellet-les-Sausses east of the Coulomp River. All are detailed in Stanley (1961, 1974) and Iwuchukwu (1968), and several of these localities on opposite sides of the Coulomp valley will be discussed in subsequent sections (Excursion day 3 *in* Appendix).

The more typical exposures of flysch facies of the Annot Sandstone crop out to the north of Le Ruch. The formation in the region in the Lac d'Allos-Col de la Cayolle region (Fig. 10) is detailed in Kuenen et al. (1957) and Stanley (1961, 1963); several exposures of the thick (>600 m) alternating well-indurated sandstone-schist sequence in the vicinity of the Lac d'Allos will be discussed (Excursion day 4 *in* Appendix).

Contes Region

Thick friable sandstone beds similar to those at Annot, although not as well exposed, occupy about 17 km^2 between the villages of Contes, Berre-les-Alpes and Coaraze in the Alpes Maritimes (Fig. 11). These NNW-SSE trending units, whose stratigraphic thickness exceeds 350 m, crop out above the Calcaire nummulitique-Marnes bleues sequences in the syncline cut by the Paillon and Paillon de Contes rivers; the western upturned and deformed limb of the syncline west of the Paillon has undergone considerable erosion. Field data have been collected at about 70 localities within the Contes - Berre-les-Alpes - Coaraze area and at the Cime du Savel sector to the north (Stanley, 1967); paleocurrents also have been measured by Guernet (1960) and Bouma (1962). The numerous small roads traversing the area permit good examination of the various stratigraphic zones of the formation (Excursion day 1 *in* Appendix).

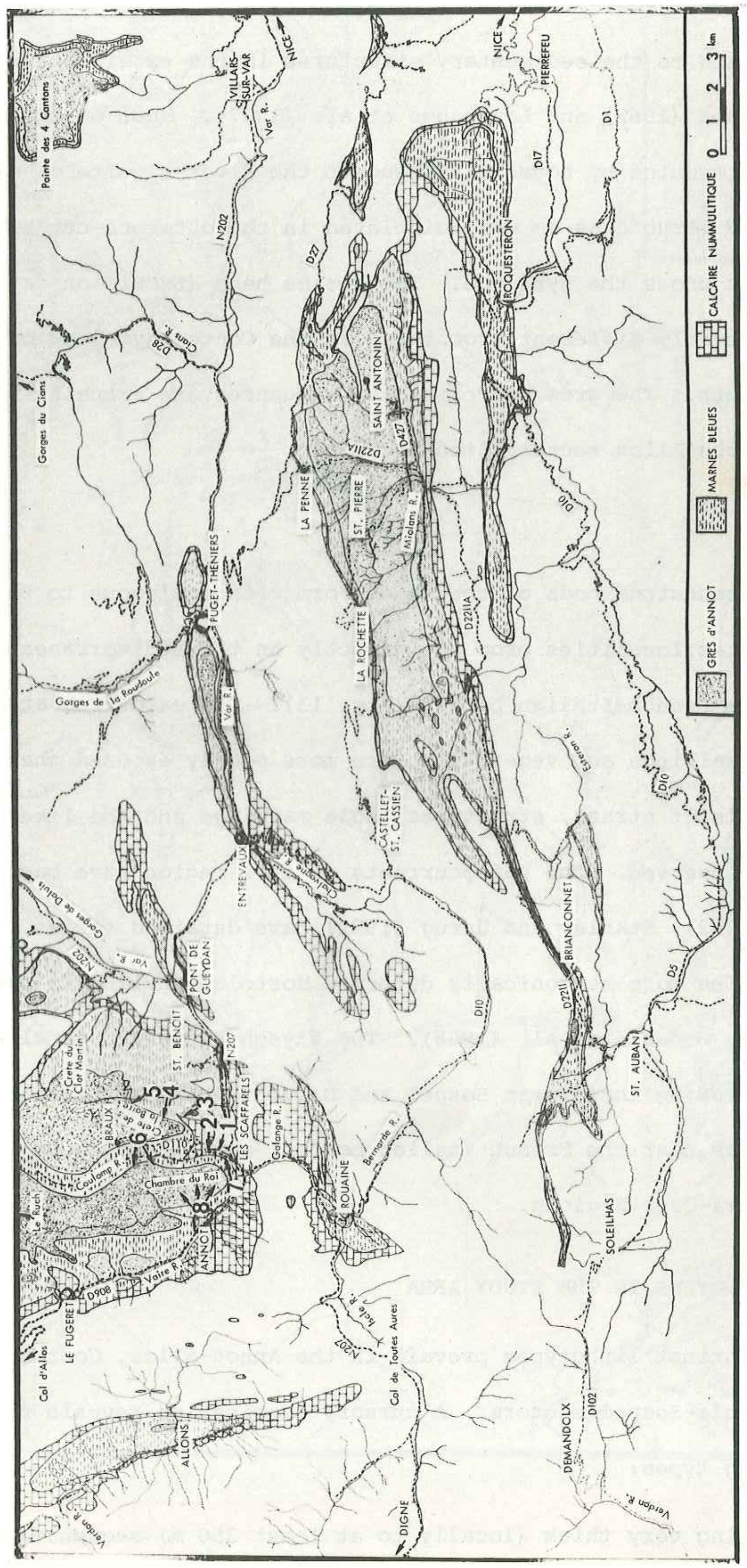


Fig. 9. Simplified geological map (from *Nice* and *Castellane* maps, 1:80,000) showing the Annot Sandstone at its type locality near Annot (Excursion day 3); also lateral equivalents at Pugét-Théniers and St. Antonin.

The Annot Formation presenting the more typical flysch facies is well exposed in the large Peïra-Cava syncline to the north (Fig. 12). Considerable attention has been paid to the sedimentary structures in the excellent exposures of this region by Bouma (1962) and Lanteaume et al. (1967). Much of the basic work on turbidites presented by Bouma was based on the diverse suite of strata types and sedimentary structures so well displayed in the outcrops cut by the network of roads that cross the syncline. The facies here (Excursion day 2 *in* Appendix) are considerably different from those in the Contes syncline only about 5 km to the south. The grès de Peïra-Cava sequences are actually more similar to those in the Allos sector cited above.

Menton-Mortola Area

Thick, friable sandstone beds of the Annot Formation analogous to those of the Annot and Contes localities crop out directly on the Mediterranean coast in synclines near the French-Italian border (Fig. 13). The exposures at Menton, largely covered by dwellings and vegetation, are more poorly exposed than those at Contes, but details of strata, structures, sole markings and the like nevertheless can be observed. The paleocurrents of this region have been surveyed by Bouma (1962); Stanley and Unrug (1972) have detailed facies, geometry and paleocurrents. The more tectonically deformed Mortola syncline to the east has been described by Bodelle et al. (1968). The flysch facies in synclines north of Menton, including those near Sospel and Olivetta (exposures near the Bevera and Roya rivers near the French-Italian border) appear analogous to those of the Allos and Peïra-Cava Regions.

DOMINANT LITHOFACIES TYPES IN THE STUDY AREA

Several very distinct lithotypes prevail in the Annot-Allos, Contes-Peïra-Cava and Menton-Mortola-Sospel sectors. A cursory examination reveals the following contrasting types:

1. A facies comprising very thick (locally to at least 350 m) sequences of poorly to moderately-well stratified coarse- to medium-textured sandstone strata

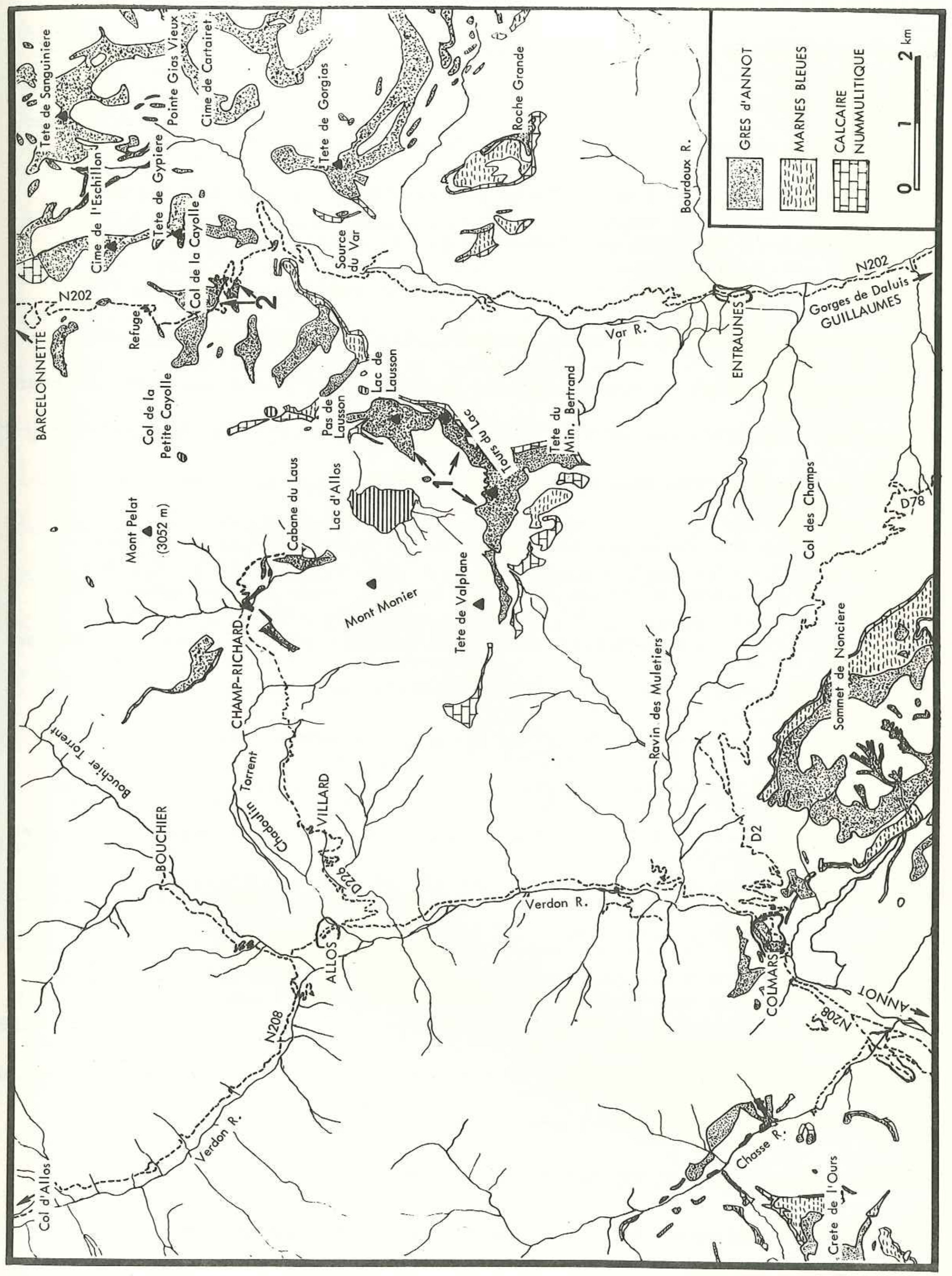


Fig. 10. Simplified geological map (from *Allos* map, 1:50,000) showing typical *grès d'Annot* flysch localities in the Lac d'Allos-Col de la Cayolle region (Excursion day 4).

with few, thin intercalations of shale or alternating thin sandstone-shale units is herein termed *type 1* facies (Fig. 14 A). Pebbles and granules of diverse crystalline rock types abound and, in some instances, are concentrated in sufficient numbers to form distinct conglomerate beds. The beds of the thick (often >10 m) units are either sharp-based or present large load or other soft-sediment deformation features at their base; graded bedding does not prevail and sole markings are generally poorly developed. Small to very large mudstone clasts occur in the thick sandstone bodies; contorted units of shale and sandstone are not uncommon between, or within, the sandstone strata. This facies is prevalent in the Menton and Mortola areas along the Mediterranean coast, and also occupies the greater part of the Contes syncline (Excursion day 1) and the region west of the Coulomp River near Annot (Excursion day 3).

2. In contrast to the above are the exposures of moderately well to very well stratified sequences of alternating sandstones, some of them graded, and shales. The thickness of sandstone strata is variable and, as a consequence, so is the sand-shale ratio. This lithofacies includes most of the attributes of flysch deposits so extensively described in the literature. Two subtypes are evident: a *type 2a* facies characteristically are defined by high sand-shale ratios (generally exceeds 3.0) and usually comprise some relatively thick, very coarse to medium grade sandstone units (not all of them turbidites) and shales (Fig. 14 B); a *type 2b* facies consist of thinner, micaceous sandstone and siltstone sheets (turbidites prevail) alternating with light to dark colored shale (Fig. 14 C). Stratigraphic sections displaying transitional characteristics between type 2a and b are observed. Both types are also commonly observed within the same section. Facies types 1 and 2 may interfinger, and in such case the lithologic changes in time and space tend to be abrupt.

Many of the sandstone units show good to moderate graded bedding and turbidites account for an important part of the sequence; thicker sandstone units (>2m) are often, but not always, poorly graded. These more massive strata commonly include crystalline granules and pebbles either concentrated near the

base or dispersed throughout the bed. Lenses of contorted units and conglomerates are generally less important in terms of total section thickness than in the type 1 facies. Although some thick (>10 m) coarse-textured sandstones typical of the type 1 facies are present, they usually are not the dominant stratal type in terms of total thickness, even in type 2a exposures. The friable sandstones become well consolidated toward the north (i.e., northern part of the Peïra-Cava syncline, north of Annot, north of Menton, etc.) in those areas where structural deformation has been more intense; the Marnes bleues below the Annot Formation, as well as the shales between the sandstone beds, are diagenetically altered (= schistes à globigérines) in these regions.

Examples of type 2 sequences are exposed on the eastern part of the Contes and Annot (east of the Coulomp River) synclines (Excursion days 1 and 3), and dominate the formation in the Peïra-Cava and Allos sectors examined on Excursion days 2 and 4; they also dominate exposures in the Sospel region north of Menton and Mortola. Details of these major lithofacies types are illustrated in later sections.

A REVIEW OF SUBMARINE VALLEY SEDIMENTATION

Before detailing the specific Annot Sandstone facies considered in this study, it is worthwhile to summarize some of the major aspects of slope and base-of-slope channels and the sediments that fill them. A morphological survey of the world's modern slope province, presented in the comprehensive region-by-region review by Shepard and Dill (1966), clearly demonstrates that a nondissected outer margin is a rarity. Considerable advances have been made in defining general submarine slope sedimentation patterns (recent reviews *in* Stanley, 1969; Middleton and Bouma, 1973; Dott and Shaver, 1974), including processes active in slope-incised submarine canyons (cf., Shepard and Dill, 1966; Heezen and Hollister, 1971; Stanley and Unrug, 1972) and in submarine fan-valleys extending beyond canyon mouths at the base of the slope (cf., Nelson and Kulm, 1973; Mutti, 1974; Nelson and Nilsen, 1974; Normark, 1974). Admittedly much uncertainty remains as to the details of sediment facies and processes active within deep submarine valleys on the slope proper.

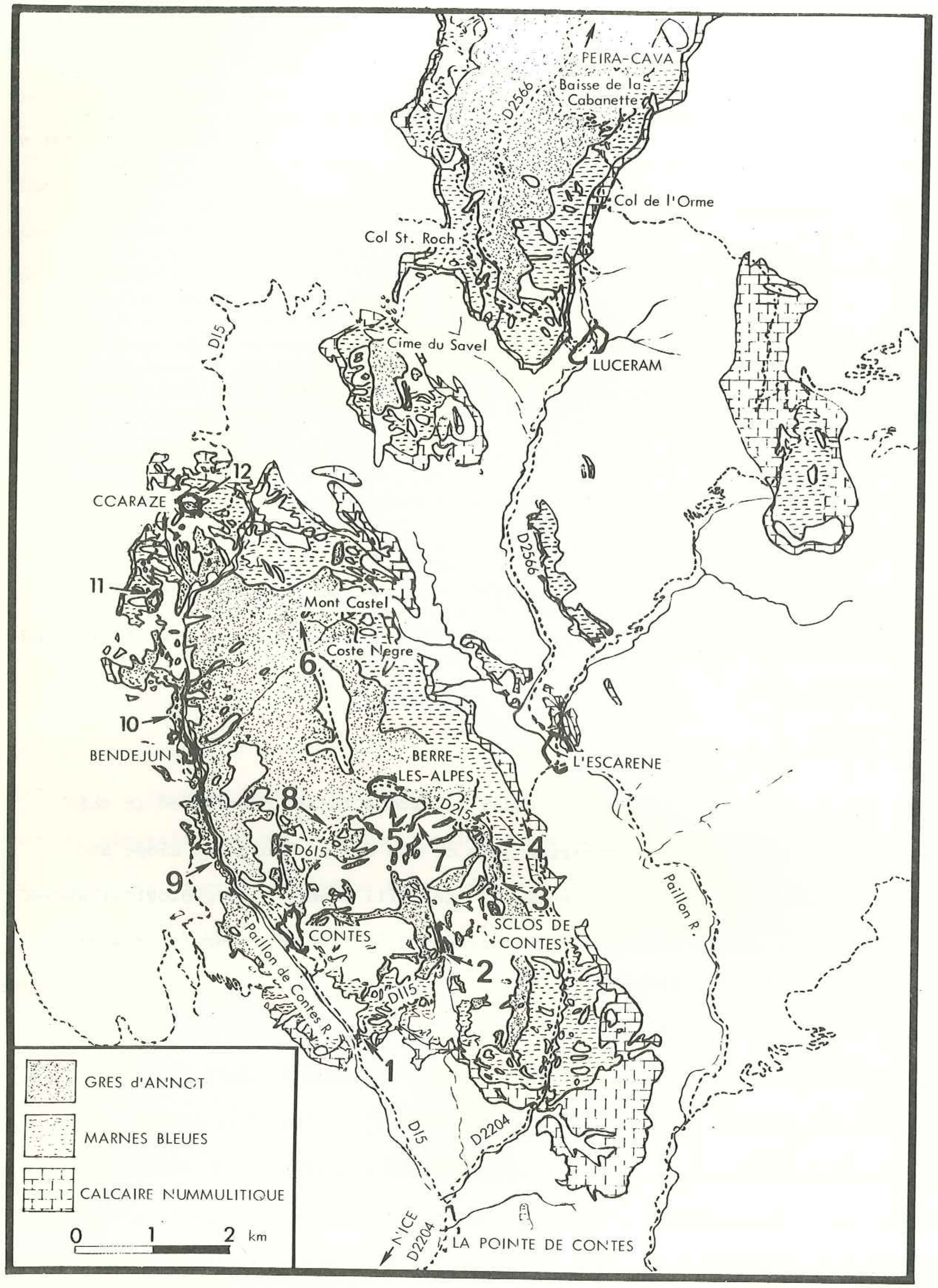


Fig. 11. Simplified geological map (from *Menton-Nice* map, 1:50,000) showing Annot Sandstone *s.l.* in the Contes syncline (Excursion day 1) and at the Cime du Savel and southern part of Peïra-Cava area (Excursion day 2).

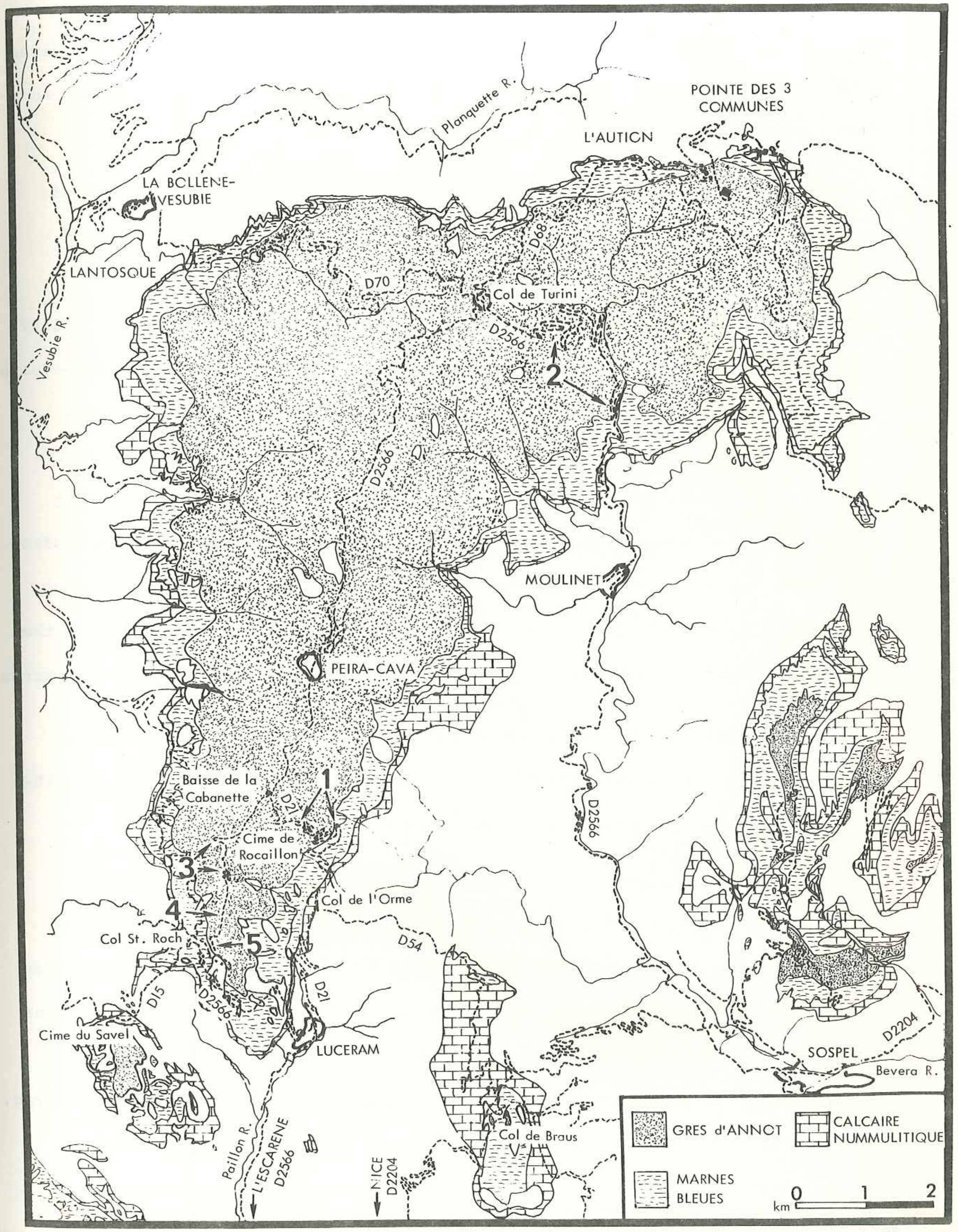


Fig. 12. Simplified geological map (from *Menton-Nice* and *St. Martin-Vésubie* maps, 1:50,000) showing sandstone localities in the Peïra-Cava region (Excursion day 2).

Modern canyon sedimentation patterns have been examined most closely in the upper reaches of canyons, but the recent increase in submersible survey dives is providing much-needed information on mid- and lower-slope sectors as well as on submarine fans and basin plains.

The term *submarine canyon* pertains to a straight to sinuous steep-walled V- or U-shaped valley cut into a slope which frequently heads on a shelf and generally extends well onto the basin (or abyssal) plain below. The term *submarine valley* has a much broader connotation and refers to almost any variety of sea-floor depression. As might be expected, canyon deposits tend to be massive and have a high thickness:width ratio primarily because of accumulation in a relatively fixed slope depression. The majority of canyons trend parallel or subparallel to the slope, and display primary dips of 5° to 10° or more along the axis cut into the uppermost slope; greater slopes (to 30° and more) are often encountered locally along the uppermost reaches of the basin margins and along steep canyon flanks. Slopes decrease to less than 1° on basin aprons beyond the topographic break and decrease in gradient which define base-of-slope environments.

The most obvious characteristic of submarine valley fills, regardless of texture, composition or geographic-geologic setting, is their downslope trending, straight to sinuous, shoe-string channel geometry.

Like fluvial and some shelf channel deposits (cf., Peterson and Osmond, 1961; Rigby and Hamblin, 1972), submarine valley fills tend to be coarser than the sediments (in this case, intercanyon slope and fan deposits) with which they interfinger. These latter silt and clay sequences comprise enhanced proportions of both hemipelagic and mud turbidites (Piper, 1972; Rupke and Stanley, 1974) as well as well-stratified overbank turbidite sheets. In sum, texture and fabric, faunal composition, stratification, assemblage of sedimentary structures, and most important — *geometry*, and *spatial position within a marine sequence* — serve to distinguish canyon deposits from other types of channel deposits.

Processes responsible for moving sediments down-slope through canyons differ somewhat from those in fluvial and shelf channels. *Down-flank slumping*

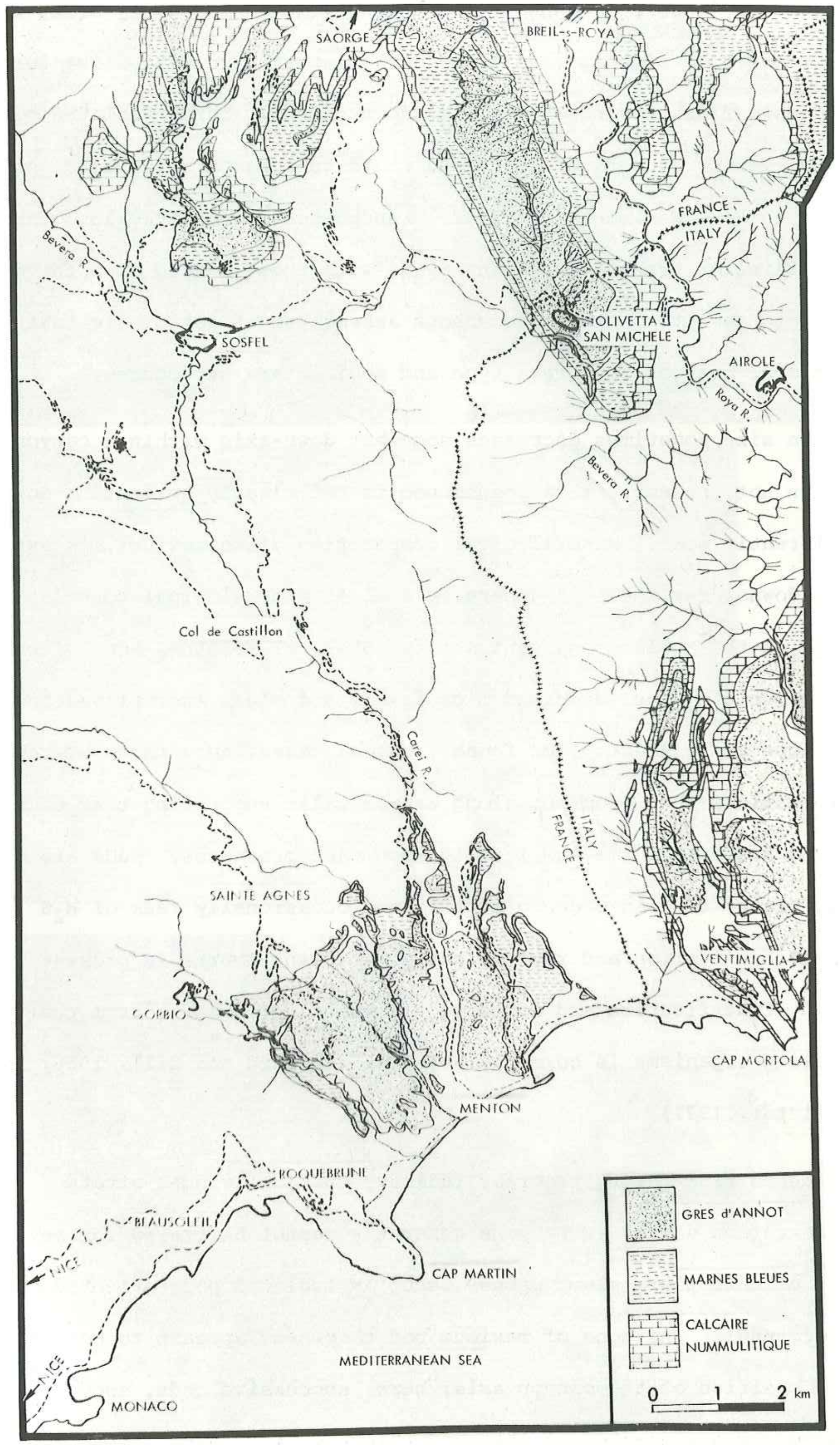


Fig. 13. Simplified geological map (from *Menton-Nice* map, 1:50,000) showing Annot Sandstone *s.l.* localities in the Menton-Mortola-Sospel regions discussed in text.

is a dominant process active in the canyons studied. The evidence for this includes sudden recorded changes of topography (Shepard, 1951; Dill, 1964) and the occurrence of contorted mud and sand strata (sometimes overturned and oriented down-flank toward the axis or downchannel), large isolated blocks of rock, mud clasts, pockets of sand, and small to large armored sand spheroids (Stanley, 1964). Sediments which are transported down-flank along the steep walls, gullies or tributary canyons merge with those moving down the canyon axis. This process results in a heterogeneous assemblage of petrologic features, and rapid lateral changes in strata type and sedimentary structures.

Grain size sometimes decreases somewhat down-axis within a canyon; more often than not, however, this phenomenon is not clearly evident. Sorting is consistently poor. Mineralogical composition, like texture, is extremely variable downslope; there is generally a close mineralogical correlation with sediments on the shallow adjacent shelf. Skeletal remains, some of which are of shallow origin, include mixed microfossil and shell assemblages indicative of downslope entrainment. The fauna, in some cases, appears to be reworked from older formations that crop out along canyon walls suggesting that submarine weathering and erosion may be locally important processes. Muds are generally green to black, rich in organic matter, and occasionally reek of H_2S (depending on degree of oxidation and rate of burial). Plant debris is present to abundant. Disturbed stratification and contorted lamination resulting from the activity of burrowing organisms is commonly observed (Shepard and Dill, 1966; Heezen and Hollister, 1971).

Evidence from coring programs indicate that individual strata (= sedimentation units) in canyons generally cannot be traced for any distance. Strata are lenticular; slump passes occur as isolated pods oriented down-flank or down-channel. The zone of maximum bed thickness appears to coincide closely with the position of the canyon axis; here, successive beds, especially of sand, are "fused" or amalgamated so that bed thickness is unusually pronounced. Graded and cross-laminated silt and sand strata occur as thin, discontinuous

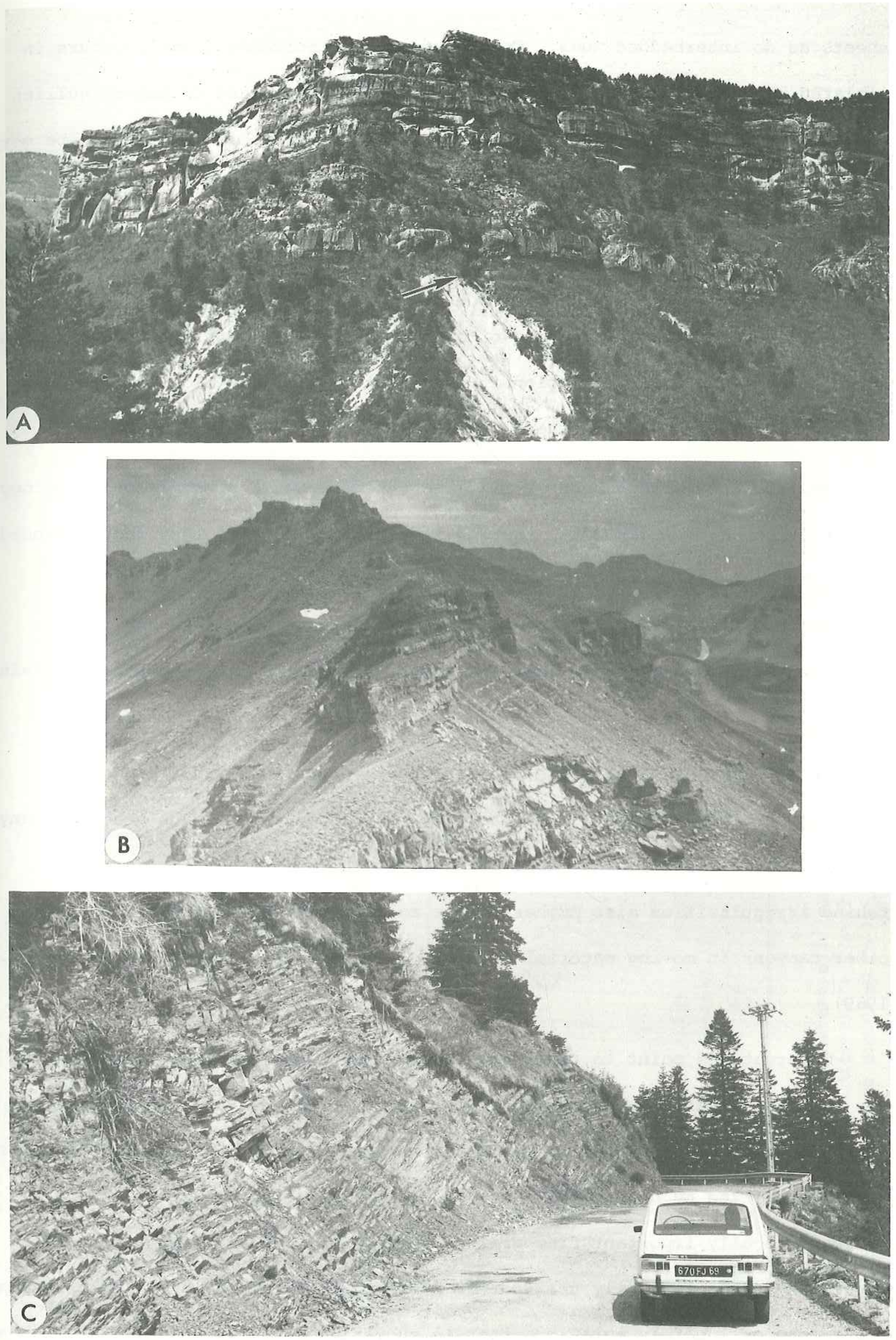


Fig. 14. Examples of dominant facies of the Annot Sandstone *s.l.* A, type 1 massive facies near Annot (arrow indicates contact with underlying Marnes bleues); B, type 2a facies in Col de la Cayolle region; C, type 2b facies north of the Col de Turini (Peïra-Cava syncline).

sheets as do interbedded muds. Coarse sediment, including gravel, occurs in isolated channel tongues in the axis of the main canyon and tributary gullies and occasionally drape the canyon flanks as well. Gravel units tend to be more localized than the sands with which they interfinger.

Gravel and boulder concentrations are found near the head and the base of flanks as well as in the axis. Downslope imbrication is occasionally observed. That gravels often lie directly above a thick mud or sand substratum suggests that the coarse fraction is being transferred downslope and is only temporarily in the position where it was sampled.

Well-defined graded beds of silt and sand are not a predominant lithology in submarine channel deposits. Coring indicates that where they occur, graded units are aerially restricted and cannot be correlated from core to core. This is in contrast with an increased proportion of graded sand and pebbly sand turbidites in submarine fans and aprons beyond the canyon mouth and basin plains.

Thin cross-laminated units, some probably deposited by normal bottom currents, are more common in canyons. Bottom photographs in the heads of many canyons reveal ripple marks, some oriented normal to the axes. Scour marks behind irregularities also emphasize the role of bottom currents in these and other canyons in moving material down-slope (Gennesseaux, 1966; Shepard et al., 1969).

Observations point to rapid but intermittent sediment transport, and to the general instability of canyon fills. There are, however, localized areas of relatively slow sediment accumulation as suggested by mottling and sections totally reworked by organisms. Subbottom profiles in submarine valleys also indicate locally important fine-grained sediment-filled pockets or "ponds" consisting of acoustically transparent hemipelagic accumulations. These fines become proportionately more important in submarine fans beyond the base of the slope.

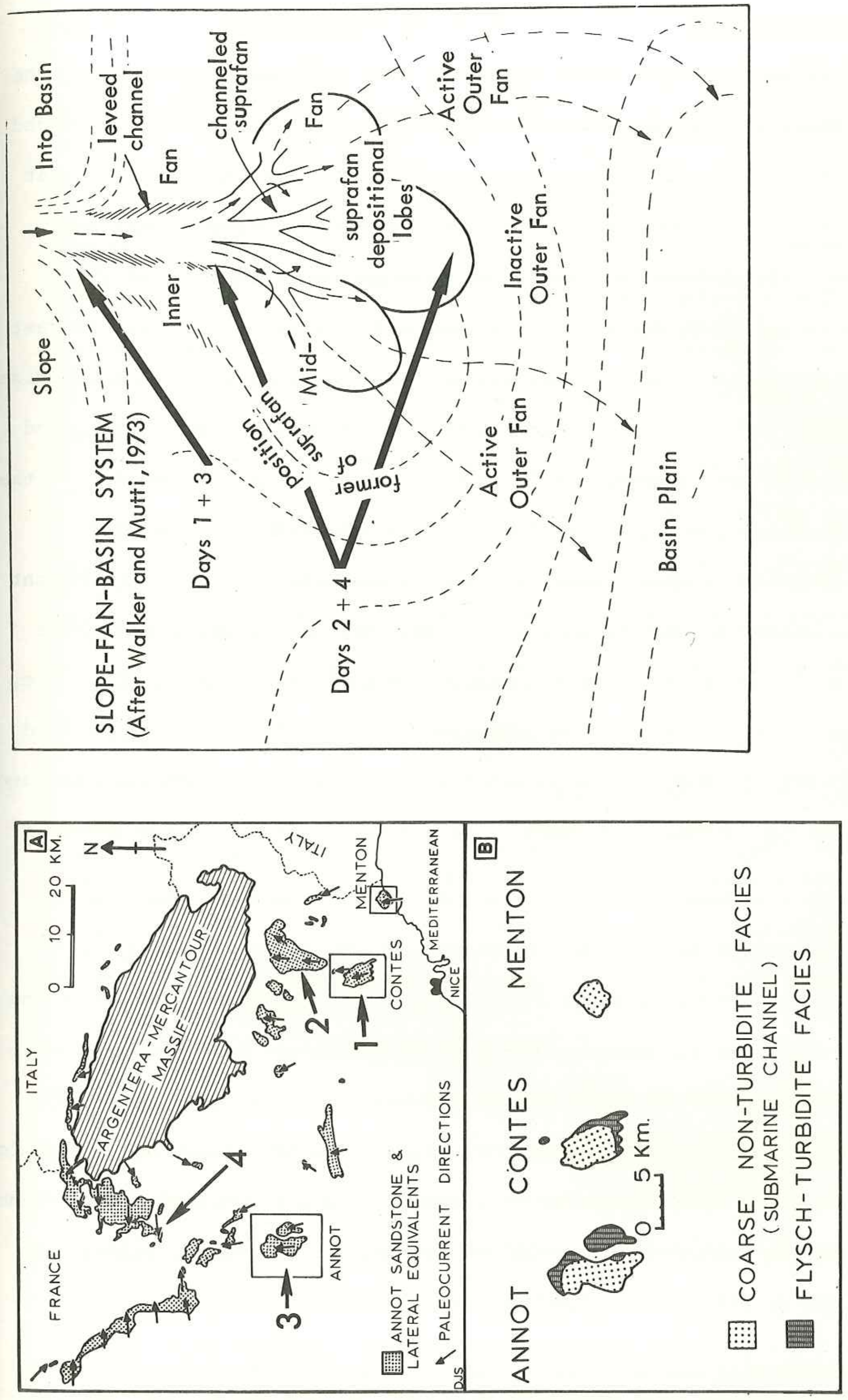


Fig. 15. Left, Annot Sandstone *s.l.* outcrop localities examined on Excursion days 1-4 showing massive (type 1) facies versus turbidite-shale flysch (type 2) facies at Annot, Contes and Menton localities. Right, Annot Sandstone localities examined in this study are interpreted in terms of submarine canyon-fan systems (model shown after Walker and Mutti, 1973).

Processes believed to affect sedimentation in submarine valleys are varied. The turbidity current hypothesis (Kuenen, 1950; Shepard, 1963) and slumping (Shepard, 1951; Stanley and Silverberg, 1969) have long been recognized as the dominant processes. However, the laterally discontinuous nature of non-graded sand and mud strata, the amalgamation of pebbly sand, sand and silt beds that comprise thick coarse channelized units, the abundance of ripple marks and laminated sand, the presence of imbricated pebbles (Gennesseaux, 1966), and erosion shadows and scour depressions (Heezen and Hollister, 1971) all suggest the importance of other transport processes: sandflow (= grain and/or fluidized flow mechanisms), debris flow, as well as bottom currents. Gravity creep and sandflow processes are of considerable importance in the canyon head and on the walls where steepest gradients prevail (Dill, 1964). Water mass movement produced by breaking internal waves, surges and tides may trigger the movement of metastable sediments resting on such slopes. Bottom current measurements in some canyons show velocities sufficiently strong to move sand; for example, velocities to 34 cm per second have been recorded in La Jolla Canyon (Shepard and Marshall, 1969). Both up-canyon and down-canyon currents have been measured, but a net downslope movement of sediment is documented in most cases examined.

The presence of graded sand and silt beds, and evidence of overbank spill-over and natural levee formation along channels beyond the base of submarine slopes together indicate the importance of turbidity currents in the formation of submarine fan wedges. Other processes should not be discounted. The presence of suspension-rich layers (low density mud turbidity currents, nepheloid layers, current-influenced hemipelagic rains of organic and inorganic aggregates) measured in water masses over the slope and base-of-slope environments may account for an important proportion of mud layers observed in canyons and adjacent slopes as well as on submarine fans.

Submarine valleys are variable in width (generally 1 to 10 km), and in trend (straight to sinuous). The sinuous form becomes pronounced beyond canyon mouth at the base of the slope as a result of channel migration. Meandering of

channels is particularly pronounced on the reduced slopes of submarine fan surfaces, basin aprons, continental rises, and plains. Fan-valley walls are relatively steep (>3°) but relief is considerably reduced in comparison with that of canyon walls cut into the slope. The asymmetrical configuration of fan-valley walls results, in part, from the meandering of channels on depositional or aggradational sequences. Fan-valley networks are complex, often displaying a multiple distributary system; occasionally a braided pattern is recognized. Transverse profiles show natural levees often preferentially developed on one side of a fan-valley. In these respects fan-valleys resemble river channels crossing deltas and valleys crossing alluvial fans. It has been demonstrated that modern channel systems are to some degree dependent on postglacial changes of sea level and related marked fluctuations in the amount of sediment transported downslope. During phases of rapid sedimentation, a shifting and braided channel system develops near the apex of the fan; on fans where there is slower or finer sedimentation (such as the well-studied La Jolla fan valley), a single, relatively straight fan-valley tends to be maintained.

The idealized section across a submarine fan or apron generally depicts a wedge-shaped depositional build-up. This is not always the case, however, as exemplified by the La Jolla fan whose inner fan sector is formed by a thin cover of unconsolidated sediment over older faulted bed rock. The longitudinal profiles of submarine channels, particularly fan-valleys, tend to develop a profile in which a dynamic equilibrium exists between erosion and deposition not unlike those of river channels (Normark and Piper, 1969). Both headward erosion of canyons and increased deposition on the lower fan or apron frequently accompany a rise in sea level. Another hypothesis, that of combined axial downcutting and rim up-building, has been used to explain the enlargement of canyons in their vertical dimensions (von der Borch, 1969).

Returning to the main subject at hand, where do the various Annot Sandstone facies fit into the general sedimentation patterns summarized above? On the basis of field data, complemented by petrologic analysis, it can be shown that

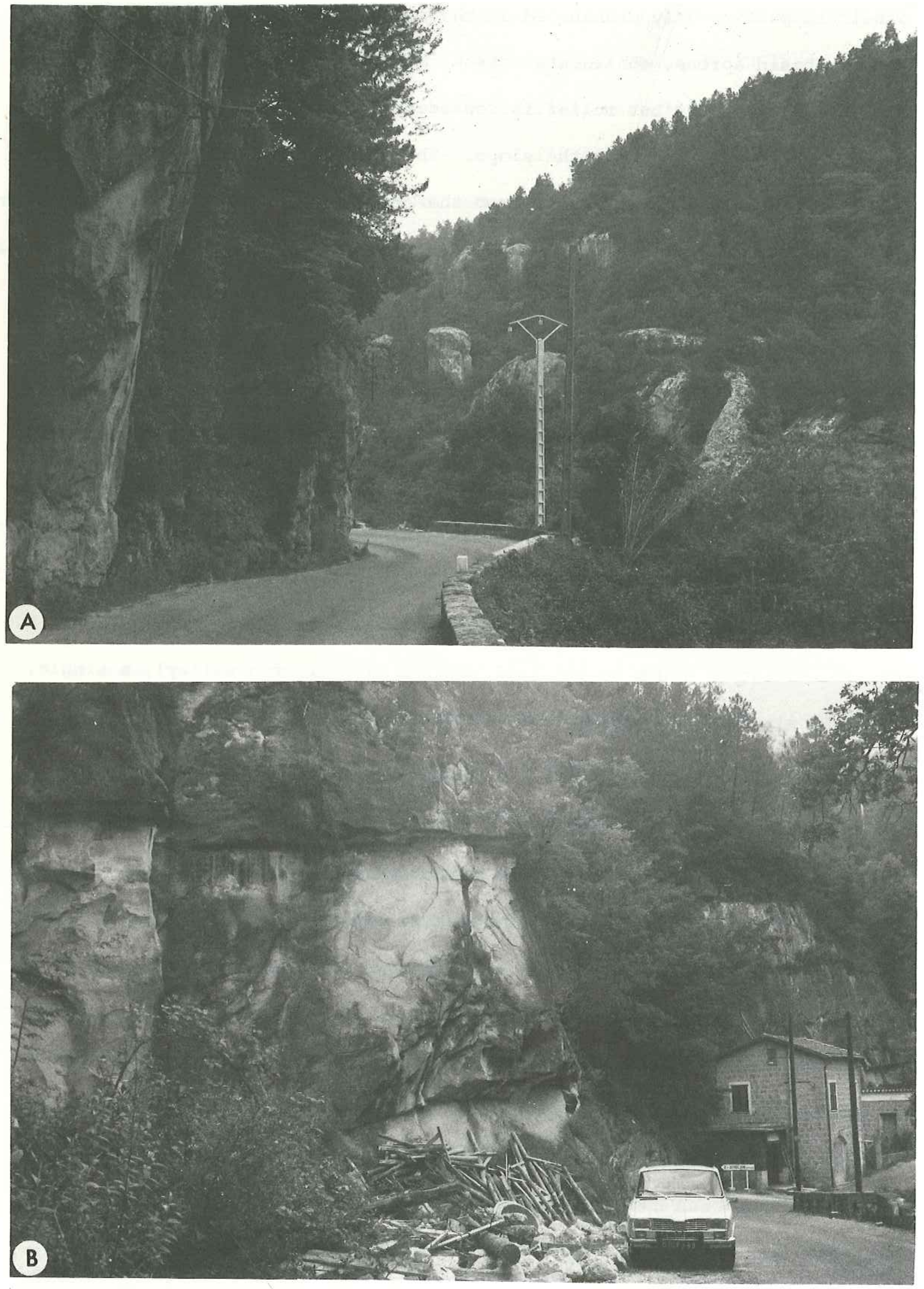


Fig. 16. Massive submarine valley (canyon) facies in Contes region, Excursion day 1 (see Fig. 11). Stops 9 (A) and 10 (B) along Paillon de Contes.

the type 1 complexes of massive, turbidite-poor sequences at Contes, Annot (Excursion days 1 and 3) and Menton are essentially comparable to some modern canyon and inner (upper) fan-valley deposits. The markedly different type 2 sandstone and shale facies in the Peïra-Cava, Allos (Excursion days 2 and 4) and Sospel regions present characteristics typical of more distal deposits, i.e., upper to lower submarine fan deposits. These interpretations can be developed in terms of canyon-fan models, such as the one depicted in Figure 15.

CANYON FILL FACIES

The type 1 facies consisting of thick sequences of coarse, massive strata at Contes (Figs. 16, 18 D), Annot (Figs. 14 A, 17, 18 A, B, 19) and Menton (Fig. 20) are remarkably similar. The most striking attribute at the three localities is the geometry and orientation of the sandstone strata as revealed by isopach maps. These depict a finger-like trend as defined by the thickest massive sandstone strata, in each case oriented essentially NNW-SSE (Figs. 21, 22). Other maps depict the three-dimensional arrangement of the thickest pebble-bearing beds which parallels this N-S trend; the paleocurrent directions measured in the massive sequence show, for the most part, a northerly-oriented dispersal path (Figs. 21; lower, 22 A). The massive sequences west of the Coulomp River at Annot and those at Contes can be traced 8 km and 6 km, respectively, along the paleoslope. The width of the linear belts formed by the thickest units is little more than 1 km wide.

The sequence west of the Coulomp River at Annot consists of massive wedge-shaped sandstone strata with only minor intercalated shale units. An E-W profile across the thick bundle of strata shows that the base of the formation is concave-up (Fig. 23); the sandstone exposures at the base of the section truncate the underlying shales (arrow, Fig. 17 C). The formation reveals essentially similar attributes at Contes and Menton. Regional mapping at Annot and Contes indicates a progressive thickening, then thinning, of sandstone from south to north; an increase northward in the proportion of shale intercalations is also observed, i.e., along the paleoslope trend. These changes can be

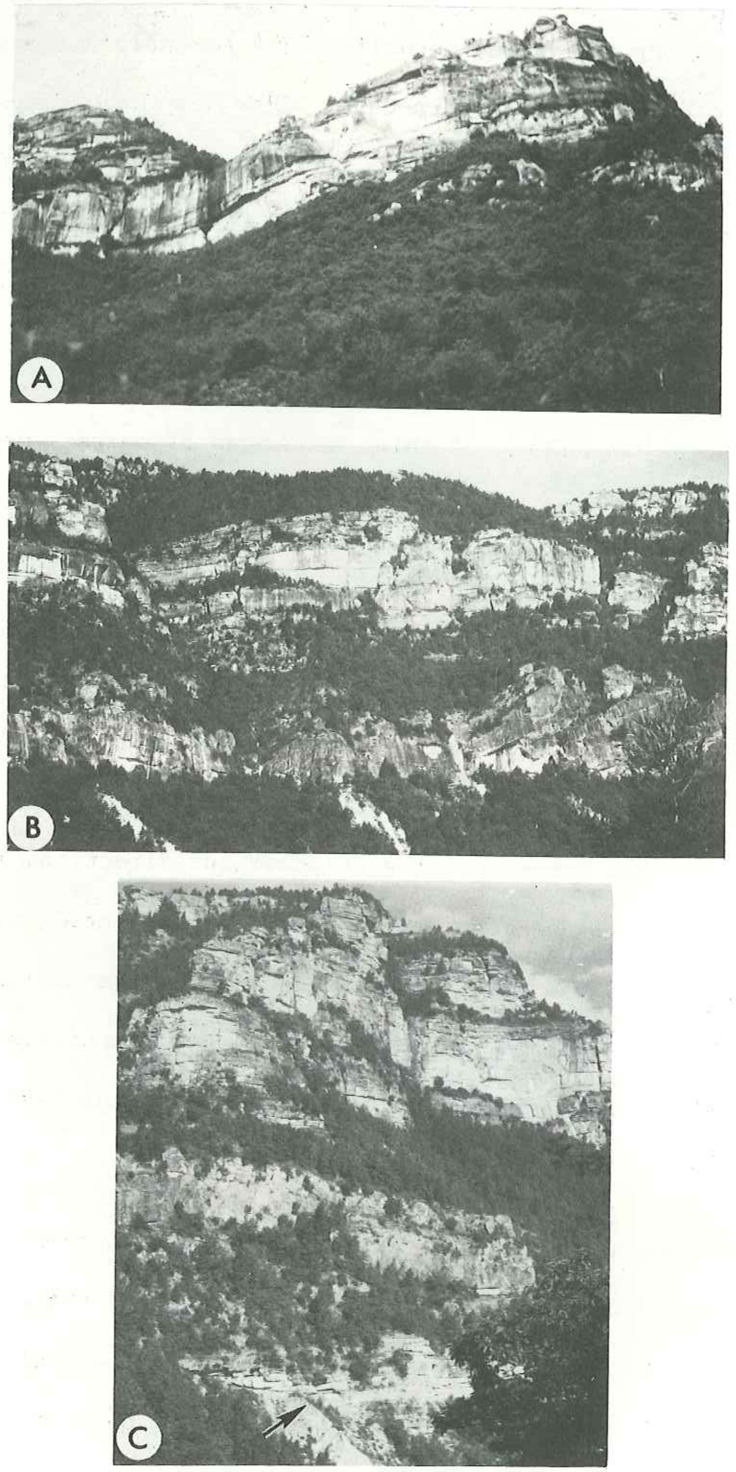


Fig. 17. Massive submarine valley (canyon) facies in Annot region along Coulomp River, Excursion day 3 (see stops 2, 6, 8 on Figs. 9 and 22). A, well-stratified sequence at Chambre du Roi locality at southern end of Annot syncline; B, irregular stratification and evidence of large-scale slumping in sandflow units; C, arrow shows truncation of Marnes bleues by pebbly sandstone deposits near axis of Annot Canyon (after Stanley, 1974a).

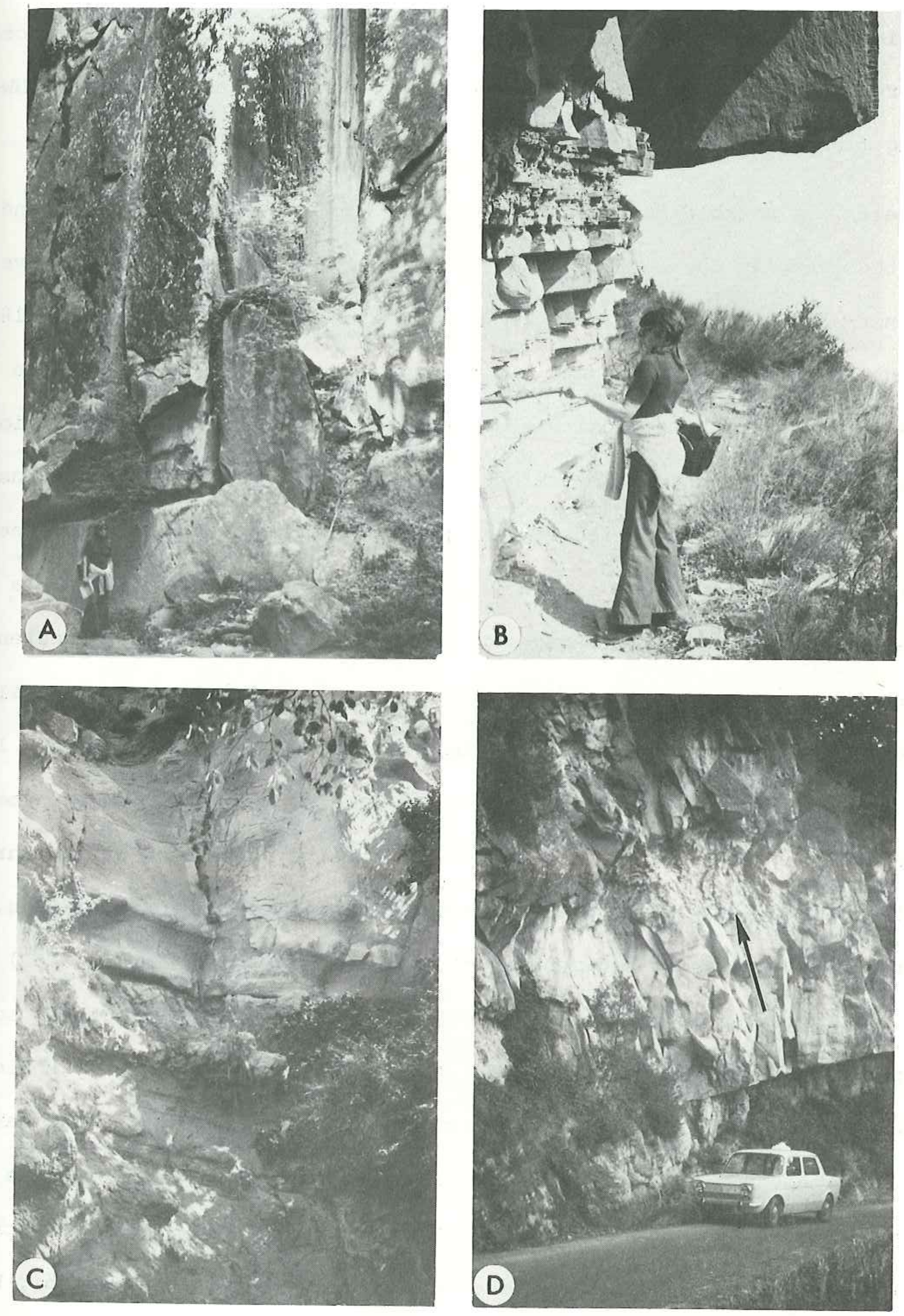


Fig. 18. Massive submarine valley facies. A, B, Chambre du Roi section, stop 8, Excursion day 3 (see Fig. 22), showing thick (>10 m) amalgamated sandflow deposits and thin turbidite-shale sequence between much thicker massive beds; C, sandflow deposit at Rouaine, south of Annot; D, chaotic slump (arrow) in sandflow unit in Contes area (after Stanley, 1974a).

observed between Rouaine (Fig. 18 C) - Chambre du Roi (Fig. 18 A) and Le Ruch to the north, and also between Contes and the Cime du Savel (top, Fig. 21). The diminution of sandstone thickness and increase of shale interbeds increases even more rapidly east and west laterally away from the margins of the NNW-SSE trending finger-like belts.

There is a notable lack of lithologic uniformity from bed to bed, and no two beds display the same sequence of structures and textures. Massive sandstones are irregularly- (Fig. 17 B) to well-stratified (Figs. 16 B, 18 D) and range in thickness from about 1 m to over 20 m; the thicker sequences (>2-3 m) are most often composite sedimentation units representing a fusion, or amalgamation, of rapidly deposited sand and pebble mixtures. Close inspection at the outcrop shows that, with few exceptions, thick (>2 m) beds have been deposited by two or more depositional events. Successive layers within a single bed are noted as a result of changes in grain size. They are most apparent where there are concentrations of granules or small pebbles, scour-and-fill and small channel structures. Small- to large-scale slumps are also noted. In some cases the entire unit has moved *en masse*; in others, only portions of a bed involve slumping (Fig. 18 D). In short, the massive sandstones at the three localities only rarely display features typical of traction sedimentation, and the vertical sequences of sedimentary structures detailed by Bouma (1962) and others in turbidites is generally not observed. The stratal boundaries sometimes are separated by thin shale stringers. In many cases, however, only shale clasts distributed along a horizon within a massive bed record what once must have been a more continuous mud layer. Such mud layers were eroded by sandflows as indicated by the abundance of rip-up shale clasts preserved within the strata. Sometimes large sandstone blocks distributed within massive beds (arrow, Fig. 20 indicate that these sandflows were able to erode underlying semi-consolidated sands as well as mud.

The base of massive units is often irregular, revealing scour-and-fill structures and load and other forms of soft-sediment deformation; other thick

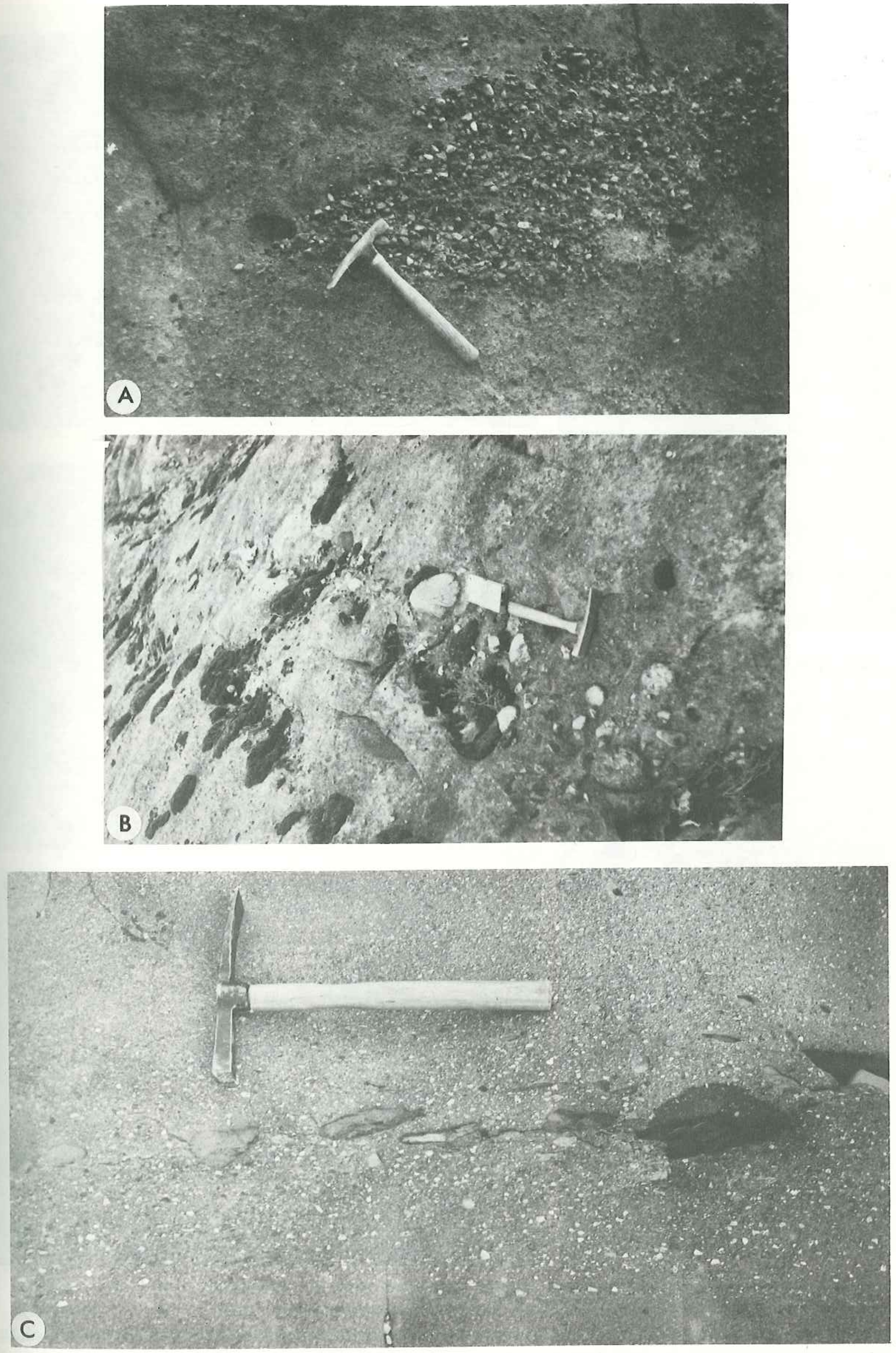


Fig. 19. Examples of pebble-rich horizons in massive sandstone sequences in the Annot region. A, B, lenses of disorganized pebbles and cobbles within sandflow deposit; C, shale clasts in coarse sandstone showing imbrication.

Fig. 20. Massive submarine valley facies in the Menton region (after Stanley and Unrug, 1972). A, thick (to >20 m) amalgamated sandflow units comparable to those at Contes and Annot; B, contorted 1 m-long sandstone block (arrow) in massive sandstone; C, horizontal lamination (matchbox gives scale) in sandstone above a disorganized conglomerate; D, pebble tongue (20 cm thick) in coarse sand layer; E, pebbly mudstone (pencil = 13 cm).

sandstones display a sharp base without notable structures and sharp top. Graded bedding, when present, is generally poor, although pebbles concentrated at the base of sandstone strata are occasionally graded or reverse graded. In some instances, pebbles within the massive beds display some form of stratification and imbrication (Fig. 19 C); more commonly, however, pebbles lack distinct stratification or structure (Fig. 19 A, B). These units are termed organized and disorganized conglomerates, respectively, by Walker and Mutti (1973). Erosional structures such as channeling are commonly observed at the base as well as within the thick pebbly sandstone strata. Pockets of gravel (Figs. 19; arrow, 20 D), shale clasts, chaotic mixes of pebbles and shale (Fig. 20 E) termed pebbly mudstone by Crowell (1957), and chaotic sandstone-shale slump masses (Fig. 20 B) and large sandstone spheroids (Stanley, 1964) are irregularly distributed within the belts of massive sandstones (Figs. 21, 22). Vague to distinct horizontal (Fig. 20 C) and convolute lamination, parting lineation, and dish structures (Stanley, 1974a) are less frequently noted, but this is due in large part to the masking effect of weathering.

The massive units described above have been termed fluxoturbidites and proximal turbidites, but more recently they have been interpreted as channelized sandflow deposits (Stanley, 1969, 1974a); a similar facies termed disorganized pebbly sandstone is described by Walker and Mutti (1973). These tongues of coarse sand and pebbly-sand mixes appear analogous to similar sediment types observed moving by creep, sandflow and debris flow processes in the heads, lateral gullies and tributaries as well as axes of modern canyons. Canyons which head close to the coast, such as those in the Mediterranean (Fig. 24) and off California (Figs. 25, 26), often trap coarse material of this type.

The depth at which these marine facies accumulated is of interest. The fact that the geometry of the massive units is similar to that of the coarse tongues in modern canyons [compare, for example, trends at Contes (upper maps, Fig. 21) with those in canyons shown in Figures 25 and 27] is important but not sufficient evidence to provide an indication of depth. The occasional planktonic

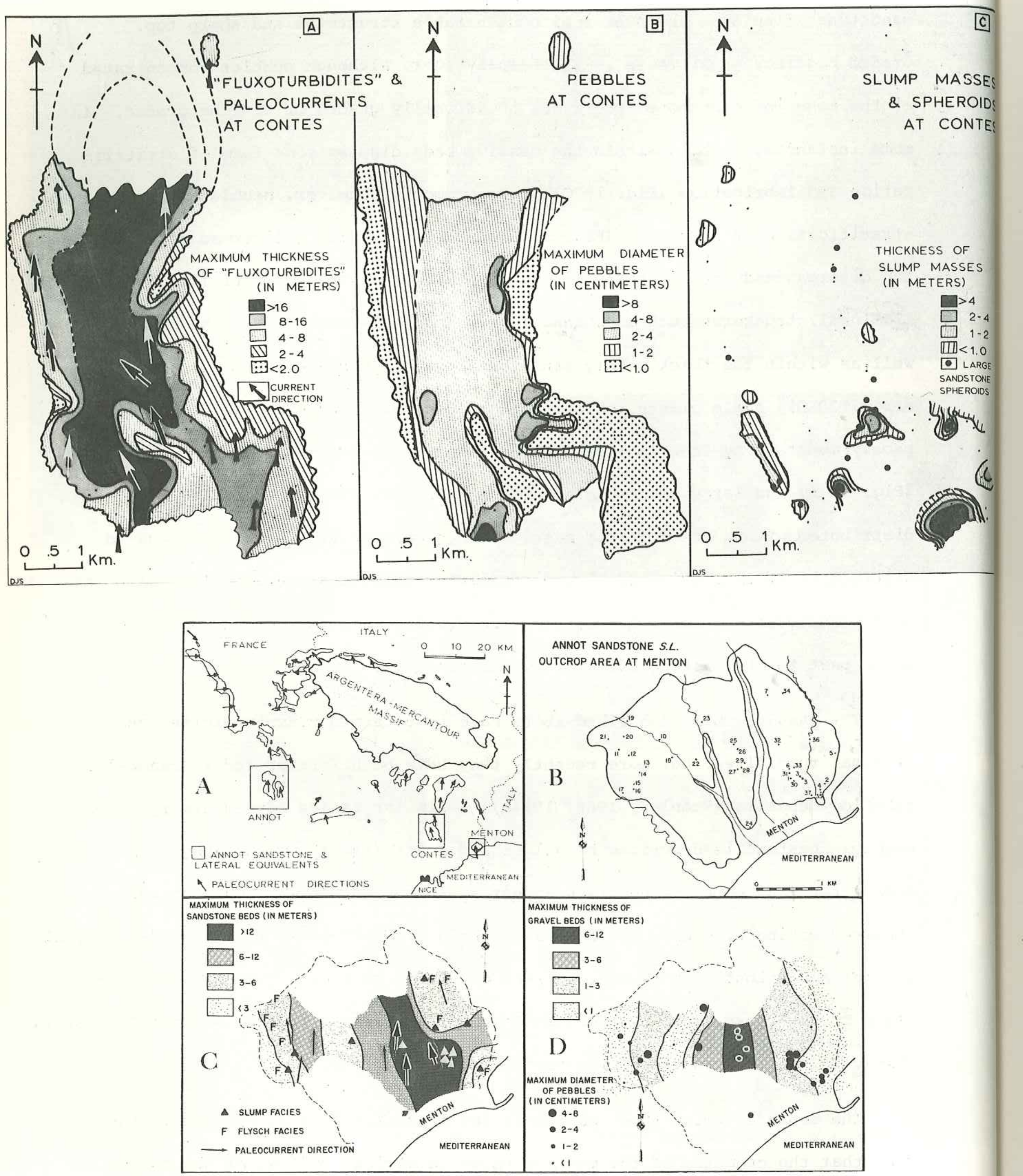


Fig. 21. Maps depicting NNW paleocurrent directions and finger-like geometry of massive (type 1) facies at Contes (upper) and Menton (lower). Note irregular distribution of slump units along the outcrop belt margins at Contes (compare with Fig. 27); after Stanley and Silverberg (1969) and Stanley and Unrug (1972).

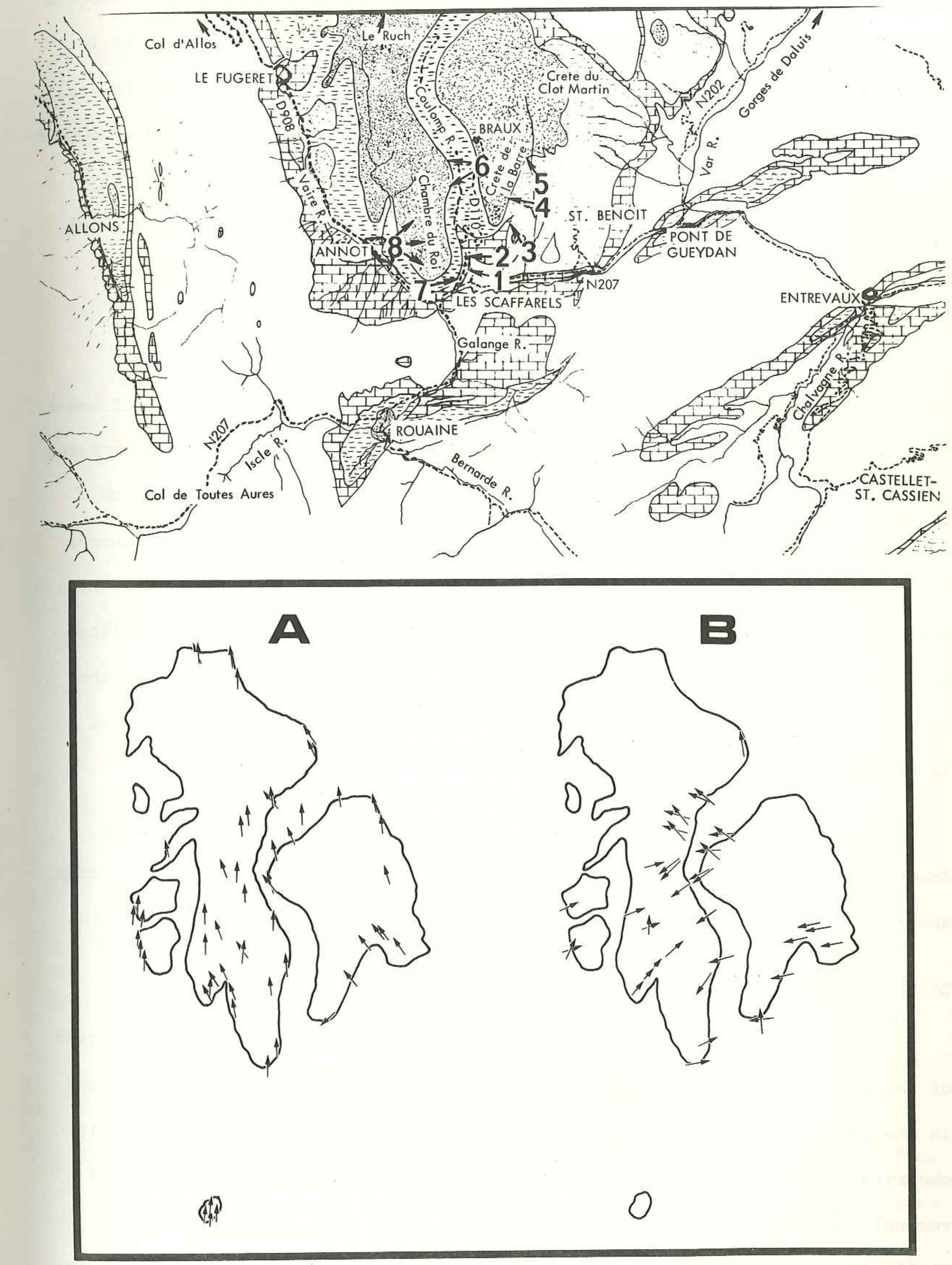


Fig. 22. Upper, map showing Annot Sandstone at its type locality and exposures examined near Annot (Excursion day 3). Lower, outline of outcrop configuration. A, paleocurrent directions based on sole markings and other structures; B, arrows depict major directions of slumping.

foraminiferal tests and coccoliths recovered in the intercalated shales indicate an open marine origin. More valuable for paleobathymetric interpretations is the mapping of trace fossil assemblages produced by benthic organisms (Stanley, 1970; Wexler, in preparation). The vertical succession of *Nereites* and *Zoophycos* assemblages at the Annot, Menton and Contes localities suggests a progressive shallowing from bathyal to possibly infra-neritic depth with time. Additional compelling, but less direct, evidence for the deep water origin of these submarine valley deposits is provided by the abundance of seaiment gravity structures within the thick units which require slopes of some importance (certainly in excess of 3°). Several points should be recalled: (a) significant gradients are needed to produce chaotic slump masses, disorganized conglomerates and pebbly sandstones; (b) these units occur along the outcrop trends which parallel the paleoslope for distances to 8 km; and (c) the delta point-sources lay several kilometers to the south [south of Rouaine (Fig. 18 C) and St. Antonin (Figs. 8, 9)]. Taking into account all of the above factors, it is postulated that the Annot Basin paleoslope lay below the infra-neritic zone and that the canyon sequences described above extended into a basin that may have been at least 1000 m deep.

These facies interpreted as axial and near-axial submarine canyon fill deposits are examined at stops 5 to 9 (Fig. 11) on Excursion day 1 (Contes area) and at stops 1-3, 6, and 8 (Fig. 22) on Excursion day 3 (Annot area).

CANYON WALL FACIES

The diversity of lithological types is even more pronounced on the margins of the linear, finger-like NNW-SSE belts of thick sandstone bodies interpreted in the previous section as canyon fill facies. Among the characteristic units observed are chaotic masses of deformed sandstones and shales. These are of variable thickness and occur between (arrows, Figs. 28 C, 29 C), as well as within (arrows, Figs. 28 B, 29 B), thick sandflow (grain/fluidized) and debris flow (includes disorganized pebbly sandstone) deposits. Well-stratified sequences of thinner alternating sandstone sheets and shale (type 2a facies) lie between

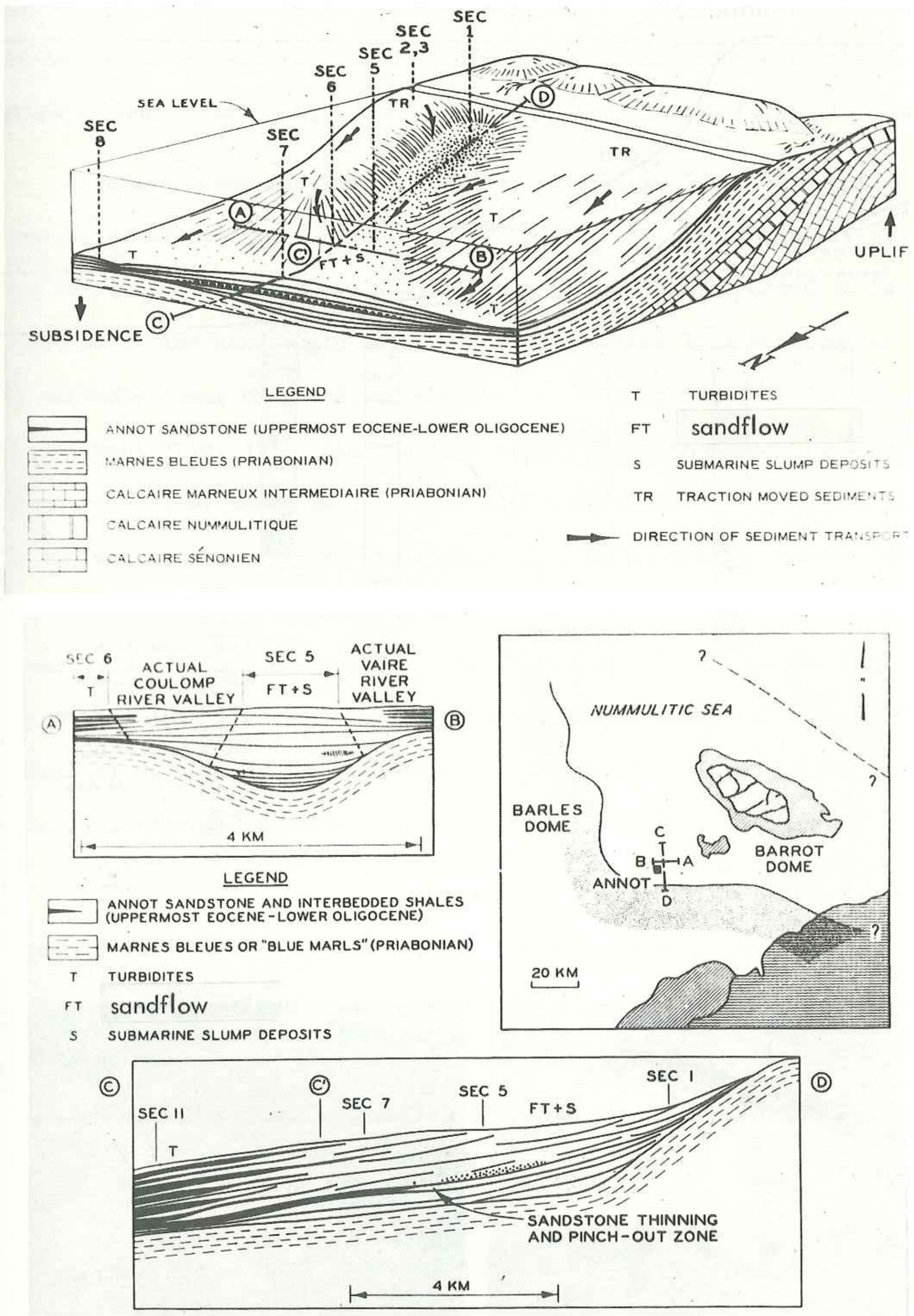


Fig. 23. Interpretation of different Annot Sandstone facies, including sandflow deposits, mapped at the Annot locality (Excursion day 3). Submarine canyon model is based on three-dimensional configuration of major facies and paleocurrents mapped in this area (after Stanley, 1961; Stanley and Bouma, 1964).

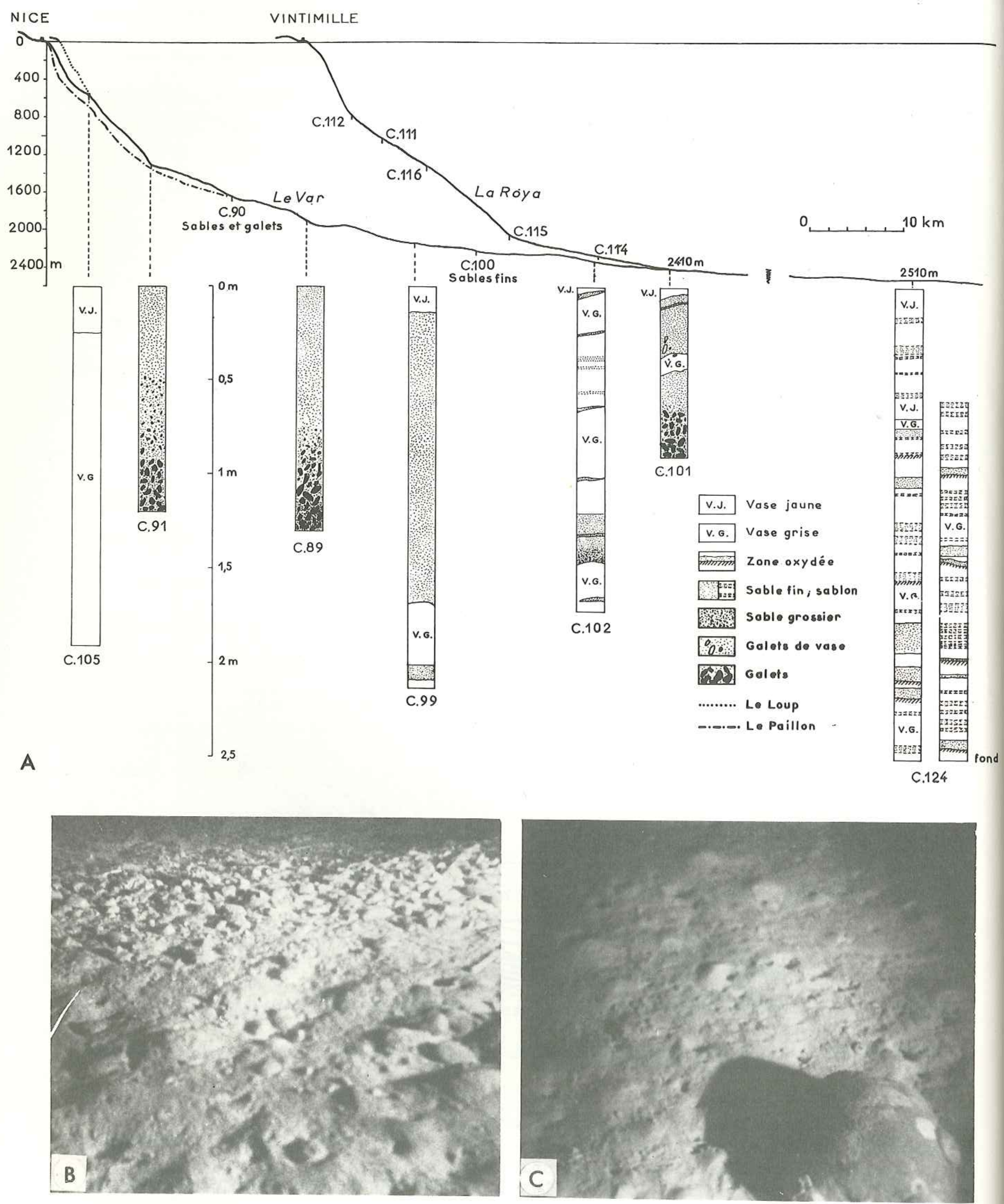


Fig. 24. A, profiles in the Mediterranean off the Nice-Vintimille region showing downslope distribution of major sediment types as mapped in cores. Note importance of pebbly sands and muds on slope and increase in proportion of sand-mud alternations beyond base-of-slope (after Bourcart, 1964). B, pebbly mud and C, large cobble on mud-floored wall and head of Catalonian canyons east of the Pyrenees (after Got and Stanley, 1974).

the thicker more laterally geometrically restricted deposits. These thinner sandstone sheets are for the most part turbidites. Many display the complete Bouma sequence including the basal (a) massive, graded turbidite divisions.

A well-exposed section on the new road (route D110) to Braux (Fig. 22, stop 4, Excursion day 3; also Fig. 30) reveals the heterogeneity of the type 2a and 2b alternating sand and shale facies exposed at the Crête de la Barre (Fig. 31). The sand:shale ratio (little more than 1.0) measured at this section is markedly lower than that of the channel fill facies (>16) exposed only 1 km to the west (Fig. 30). Disorganized pebbly sandstones, pebbly mudstones and some thick (3 m) sandflow units dominate this section (Fig. 31). The differences in facies and paleocurrent directions (Fig. 22 A) between the Crête de la Barre section and that of the massive beds forming the cliffs west of the Coulomp River (Fig. 30) are remarkable. Sole markings here, as in the eastern part of the Contes syncline (cf., Guernet, 1960), reveal anomalous paleocurrent orientations (directions trending E-W, NE-SW and even to the ESE, and *not* predominantly to the north, are measured).

The sequence is interpreted as a down-valley flank facies and may include deposits first transported downslope (northward) and then laterally (toward the west) by way of tributary and feeder channels that entered the main NNW-SSE trending valley axis occupying a position west of the Coulomp. These valley wall and axial facies interfinger in a few exposures NNW of the village of Braux. A similar geometric arrangement and interfingering of analogous facies is observed in modern canyons (Figs. 25, 27) where the predominant transport directions on slopes next to canyons are oriented downcanyon along the walls where the steepest gradients (often well in excess of 10°) are measured. Observations along modern valley walls show slump scars (arrow, Fig. 32 A) and isolated blocks (Fig. 27; arrow, Fig. 32 B) and related features attesting to the importance of failure of the metastable sands and muds on steep gradients.

The sharp contact between the Annot Sandstone channel fill and the older Marnes bleues (Fig. 17 C) which once formed the canyon walls is also a phenomenon

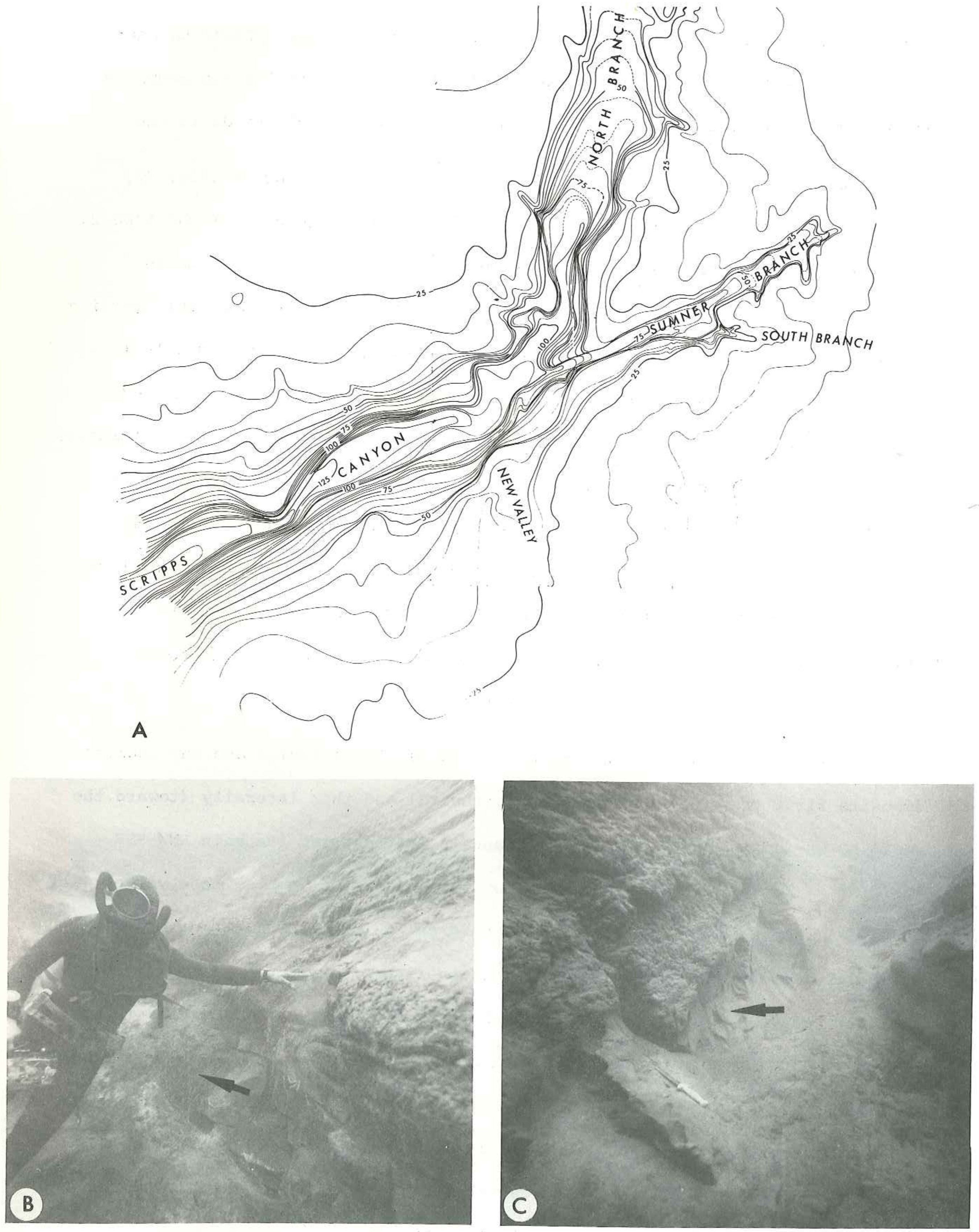


Fig. 25. A, chart of Scripps Canyon off southern California showing complex tributary network near head (depth in meters). Compare with configuration of Contes Canyon (upper, A, Fig. 21). B, sediment draping wall of Sumner Branch; sediment in gully consists of eel grass (arrow) and micaceous sand; C, base of wall (formed by Eocene mudstone, arrow) eroded by moving sediment; knife gives scale. Depth, about 20 m. Photos courtesy of R. F. Dill.

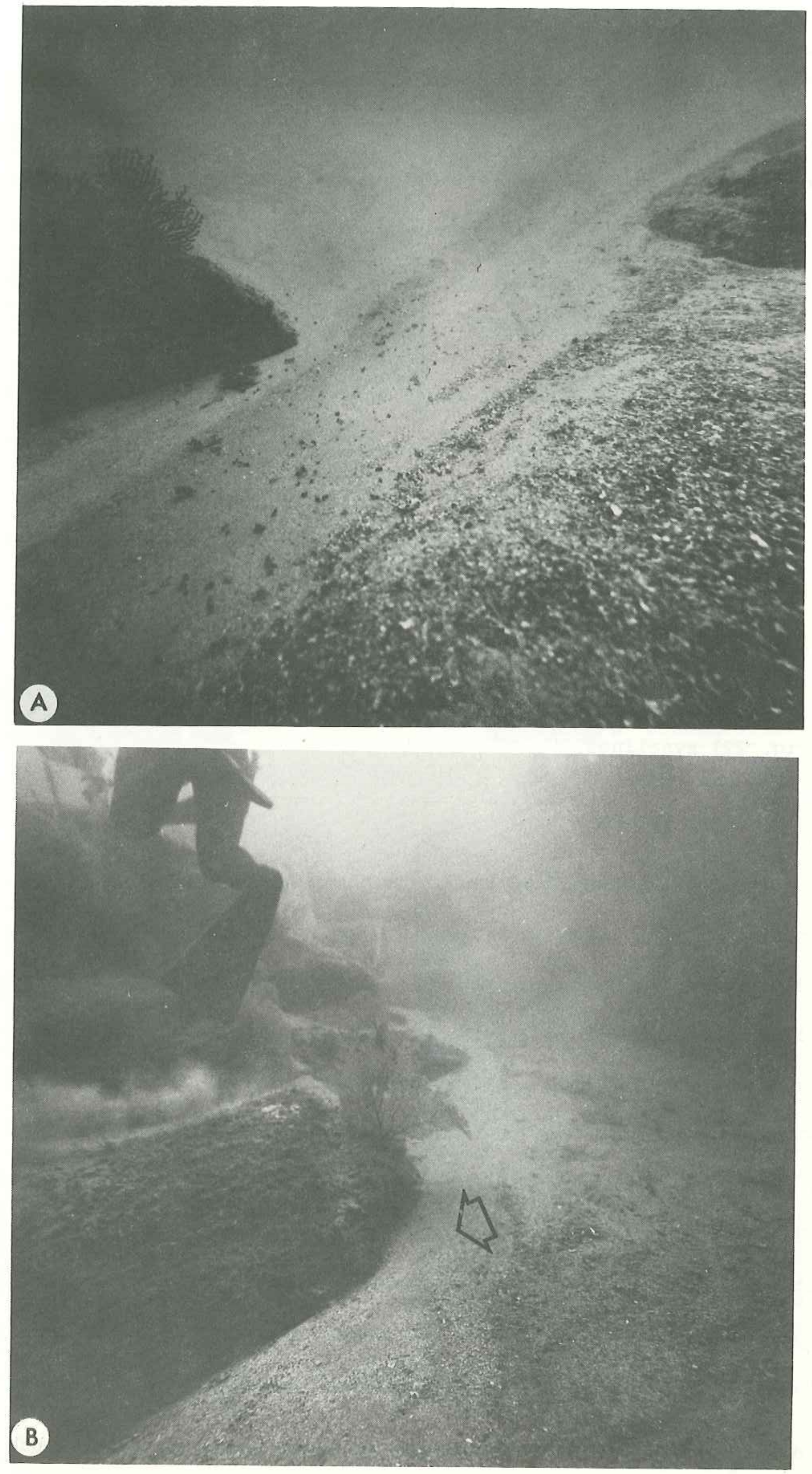


Fig. 26. Pebbly sand moving in the head of San Lucas Canyon off Baja-California (depth of about 30 m). Photos courtesy of R. F. Dill.

observed in modern canyons. An analogous situation occurs in the western Mediterranean where Quaternary to recent pebbly sand deposits move into the head and along the walls of canyons cut in stiff Pliocene clays (Gennesseaux, 1966; Got and Stanley, 1974). Observations in the Scripps Canyon off southern California show that sand moving downslope by creep, sandflow and other mechanisms actually cut into the walls (Fig. 25 B, C). This phenomenon is described by Dill (1964) and Dill and Shepard (1966).

The complex topography of the Annot and Contes canyons (cut by lateral gullies and tributaries) and the importance of downwall sediment gravity flow mechanisms together would explain (1) the irregular distribution of chaotic strata types, (2) the abundance of disorganized conglomerates and pebbly sandstones, and (3) the anomalous paleocurrent directions measured in these localities. Good examples of this facies are located on both eastern and western margins of the Contes (stops 2 and 10, Excursion day 1; Fig. 11) and Annot (stop 4, Excursion day 3; Fig. 22) synclines.

INTERCANYON SLOPE FACIES

Thinner, better stratified sandstone sheets and an enhanced proportion of siltstones and shales (type 2b facies) are mapped on the margins of the Annot (Fig. 33), Contes and Menton synclines. These sequences comprise distinct alternations of very well stratified turbidites and are interpreted as intercanyon slope deposits. This facies includes generally thin (2 to 20 cm, occasionally to 1 m) turbidites, some displaying the complete sequence of Bouma divisions (arrow, Fig. 33 B); more often the turbidites are of the b-c-d-e and c-d-e types (Fig. 33 C). The mica content of these finer grade sandstone and siltstone turbidites is high; plant matter is sometimes also important. Sole markings are unusually well developed and in the three localities indicate generally consistent and predominant northerly transport directions (Figs. 21, 22).

Trace fossil markings are particularly abundant and include a much more varied assemblage than in the case of the more massive sand-rich canyon fill

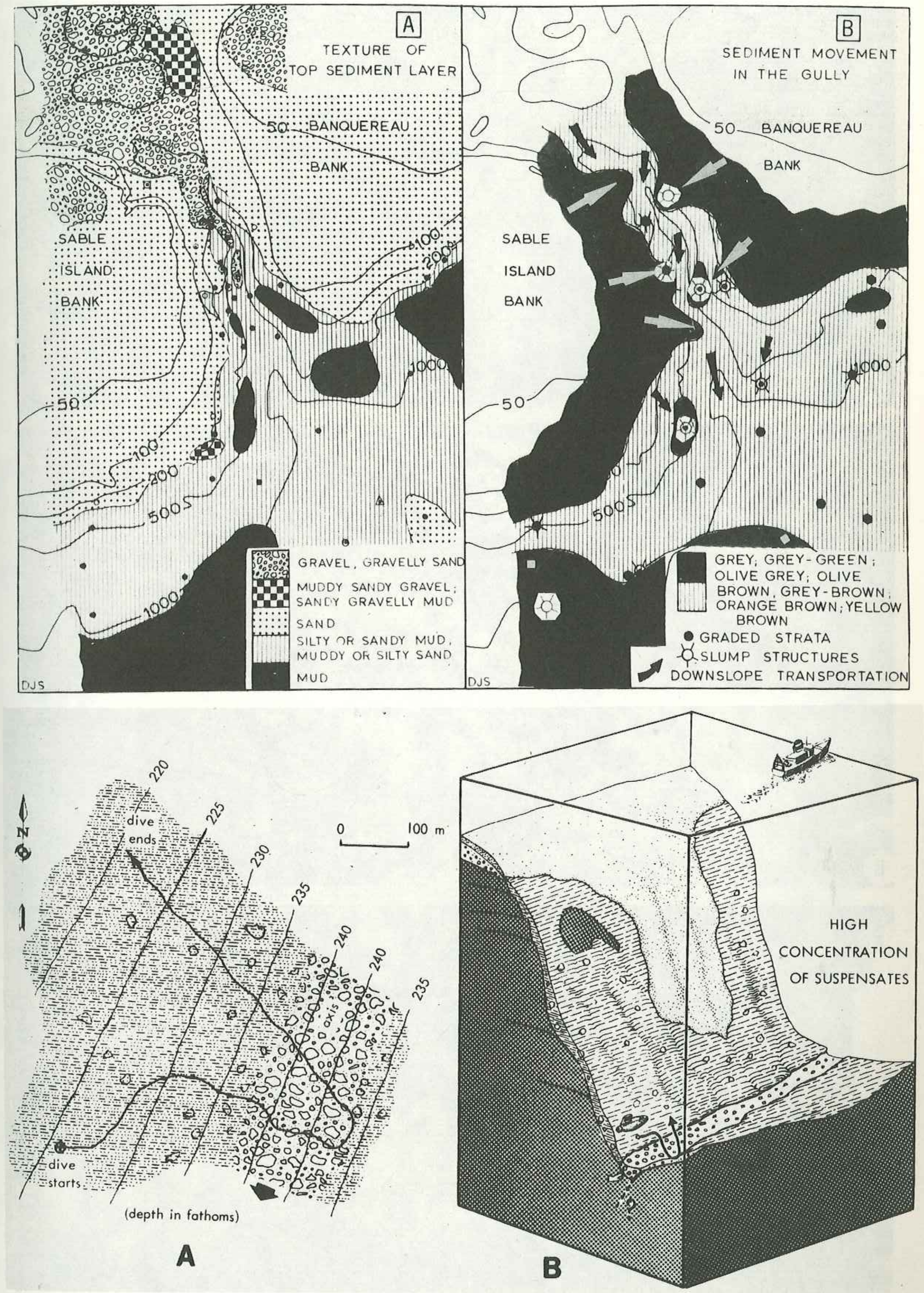


Fig. 27. Sediment facies and dominant processes in some modern submarine canyons (upper, The Gully; lower, Wilmington Canyon). The importance of slumping and sandflows on canyon walls, and of turbidity currents and debris flow processes in axis are depicted (upper, after Stanley and Silverberg, 1967; lower, after Stanley, 1974b).

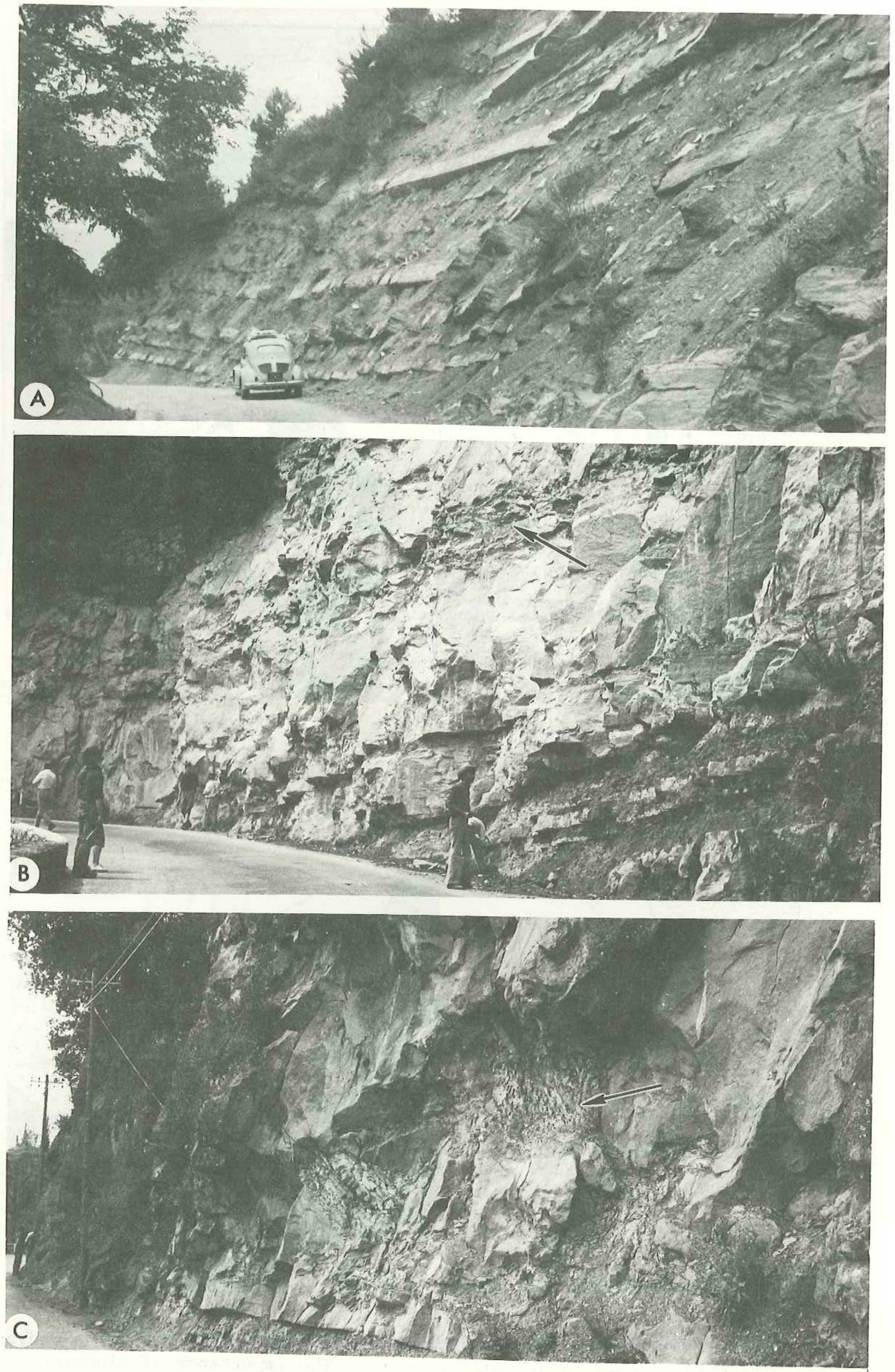


Fig. 28. Canyon wall-slope facies in the Contes region (stops 4 and 2, Excursion day 1). A, turbidite-shale slope sequence; B, chaotic slump unit within massive sandstone; C, slump at base of massive sandstone.

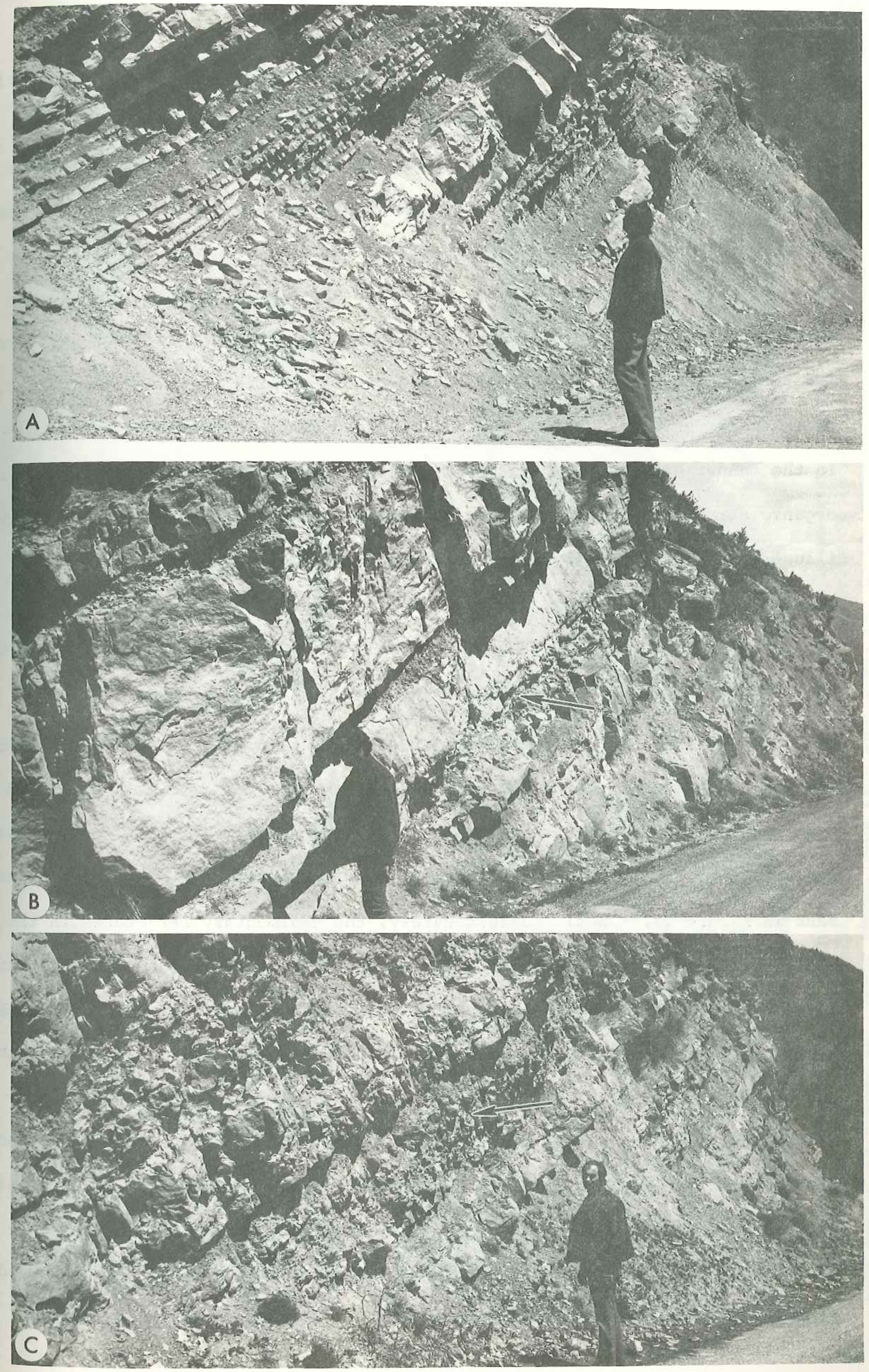


Fig. 29. Canyon wall facies in the Annot region (Crête de la Barre, stop 4, Excursion day 3). A, turbidite-shale sequence; B, chaotic slump unit within strata; C, slump between sandstone strata. Compare with Fig. 28.

and canyon wall sequences. This faunal evidence suggests a sedimentologically calmer environment and one more appropriate to the life habits of benthic organisms which graze, migrate and burrow in muddy bottoms. The majority of trails, burrows and feeding markings occur on turbidite soles; excellent examples occur north of the Crête de la Barre toward the Crête du Clot Martin and the Gros Vallon de St. Benoït (stop 5, Excursion day 3). Most of these biogenic structures, indicative of infra-neritic to bathyal faunas, are predepositional, i.e., formed on and in a soft mud bottom prior to burial by sandy turbidites. These traces were thus buried and filled (sand cast) by turbidity current flows in the manner discussed by Seilacher (1962). The variety and concentration of organic structures on modern muddy continental slopes and basin margins are well illustrated by Hersey (1967) and Heezen and Hollister (1971). Some organic structures observed in this facies of the Annot Sandstone are clearly post-depositional; this is indicated by burrows whose complex course extends through the sandstone turbidites and even between successive layers (Fig. 33 A).

The presence of occasional non-graded sand units as well as turbidites on the slope outside of canyons reflect offshelf spill-over processes (Southard and Stanley, in press) of the type occurring at present on most outer continental shelves (see, for instance, sand draping over the shelf edge off Sable Island Bank in Figure 27, A top). Unfortunately, the sedimentary structures in the shales which comprise much of this facies are poorly preserved. This section reveals both "structureless" as well as laminated types (laminae of silt grains, mica, plant fragments and clay as observed in thin section); occasional benthonic and planktonic foraminiferal tests and coccoliths are recovered. The Annot Sandstone, as in the case of many other flysch formations, presents a distinctly poor foraminiferal fauna which is surprising in that the Annot Basin is considered part of an open-marine system. The occasional vague halos observed in shale thin sections probably record the remnants of diagenetically altered, or dissolved, foraminifera.

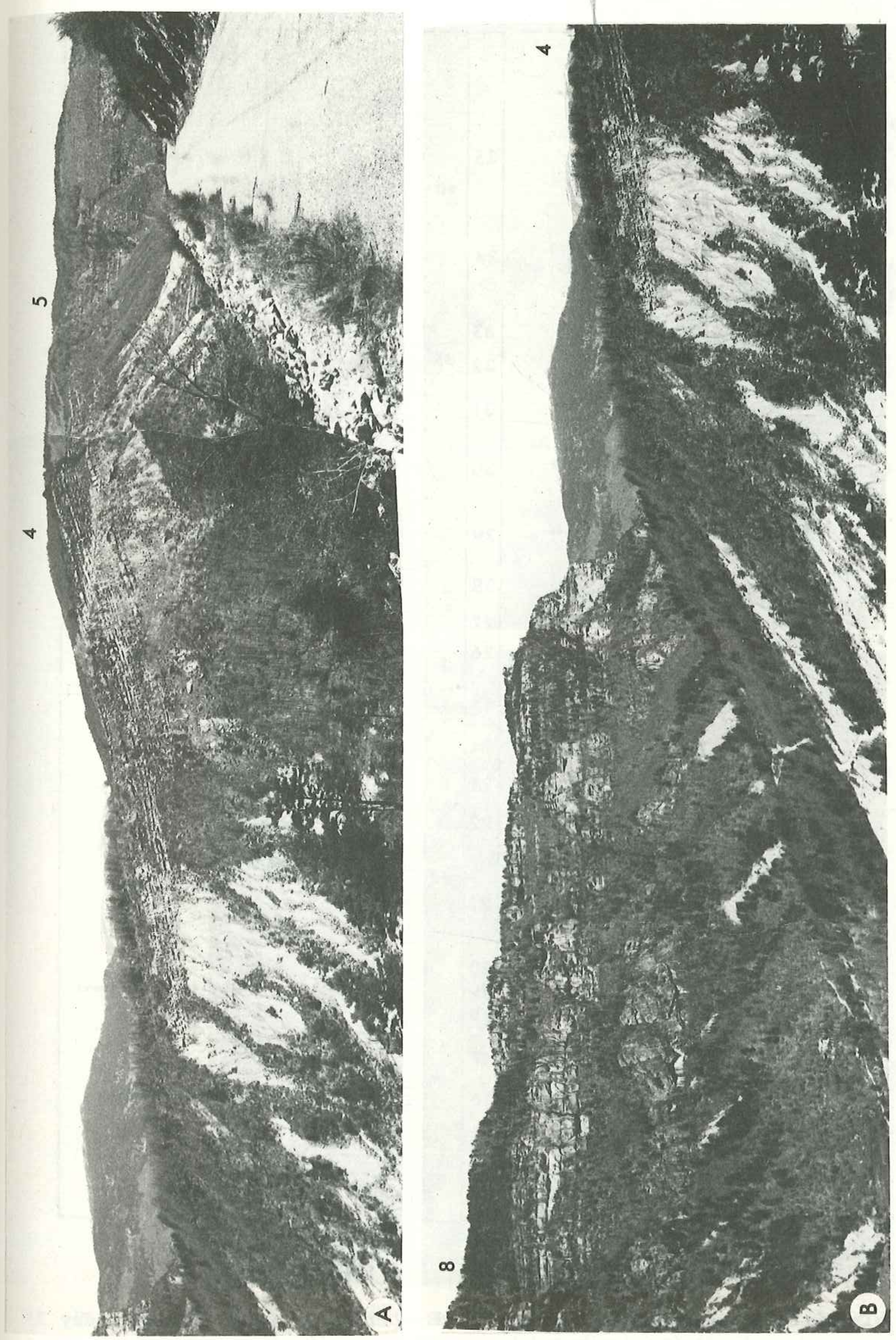


Fig. 30. Photos made at stop 3 (Excursion day 3) on the new road to Braux east of Annot. Upper, view to north; note relatively thin, well-stratified type 2 facies forming the Crête de la Barre (4 = stop 4) and Crête du Clot Martin (5 = stop 5). Lower photo, view from same area, but to the northwest; note massive type 1 facies west of the Coulomp Valley (8 = stop 8).

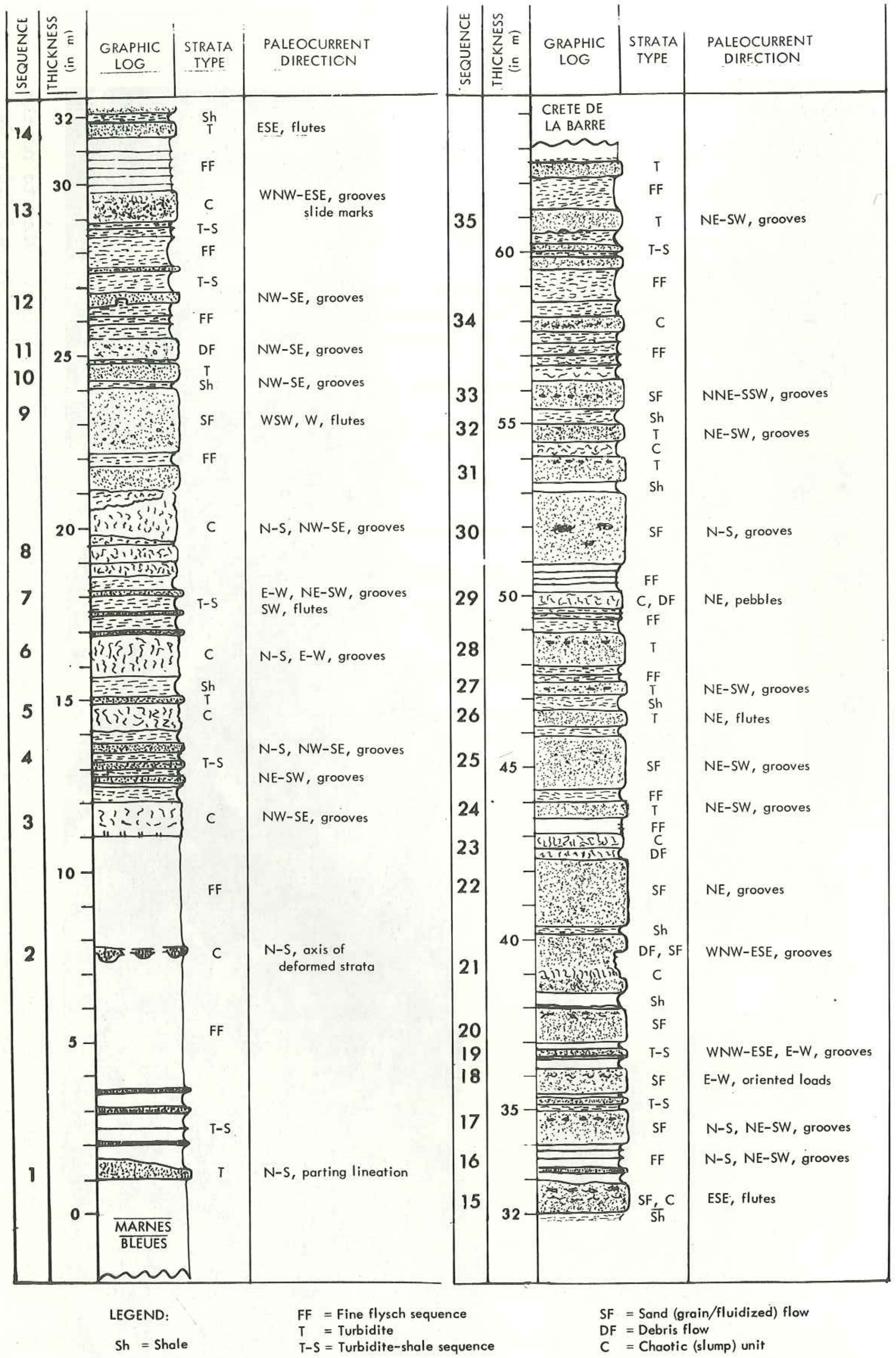


Fig. 31. Crête de la Barre section on new road to Braux (stop 4, Excursion day 3) showing canyon wall facies dominated by sandflow, debris flow and chaotic units (see also Figs. 29, 30).

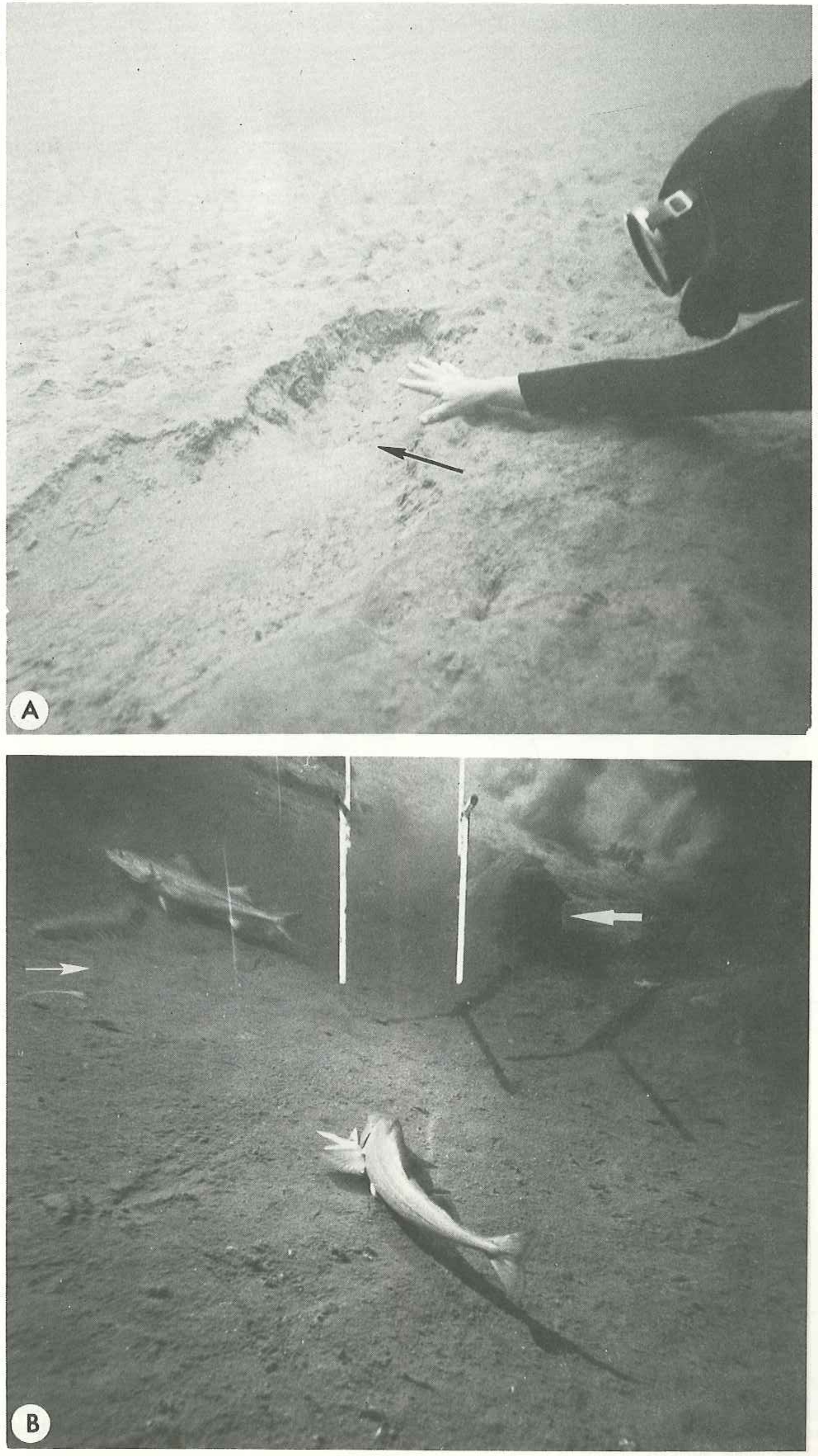


Fig. 32. A, diver on wall in Scripps Canyon pointing to possible slump scar in sandy mud; depth about 17 m. B, block of wall rock slumped onto silty clay in La Jolla Canyon; distance between rods, about 30 cm (viewed from bathyscaphe *Trieste*). Sable fish in foreground. Note crinoid heeling in current (below small arrow). Depth about 620 m. Photos courtesy of R. F. Dill.

SUBMARINE FAN AND BASE-OF-SLOPE FACIES

General

The Annot Sandstone outcrop localities at Annot, Contes and Menton discussed in the three previous sections are geographically separated from exposures further north (Grand Coyer-Mont St. Honorat, Peïra-Cava, and Sospel-Piena localities respectively) by only about 5 to 8 kilometers (Fig. 2). The formation changes markedly in aspect in that short distance and presents the turbidite-rich type 2 flysch facies typically associated with the grès d'Annot.

Although different in gross aspects, the sandstone-shale units at Peïra-Cava and in the Sospel-Piena area are genetically related to the proximal (massive, pebbly sandstone canyon-slope) type 1 facies to the south as indicated by comparable lithological composition and compatible paleocurrent directions (i.e., trending northward as detailed in Bouma, 1962; Fig. 15). These observations reflect a general dispersal of sediment from the southern (Mediterranean Esterel/Corsica) source areas northward toward the Argentera-Mercantour Massif (Fig. 5).

The paleocurrents in the Grand Coyer-Mont St. Honorat localities (not examined here but detailed in Stanley, 1961) trend generally in a northwestward direction and are compatible with transport dispersal away from the Annot-St. Antonin-Dôme du Barrot region. However, the mineralogy of pebbles and sandstones show a provenance from the southern source areas as well as from the ESE (Figs. 6, 7, 15). The paleocurrent data measured in the Annot Sandstone about 15 km further to the north, in the vicinity of the Lac d'Allos and east of the Col de la Cayolle (Fig. 10), show predominant dispersal patterns away from an easterly region (i.e., from the source area shown as A in diagram 4, Fig. 5).

These alternating sequences of turbidite and shale facies of the Annot Sandstone in the Lac d'Allos and Peïra-Cava regions present attributes which indicate depositional environments located well within the Annot Basin at, and beyond, the zone of decrease in gradient. These basin margin environments are loosely termed base-of-slope sectors.

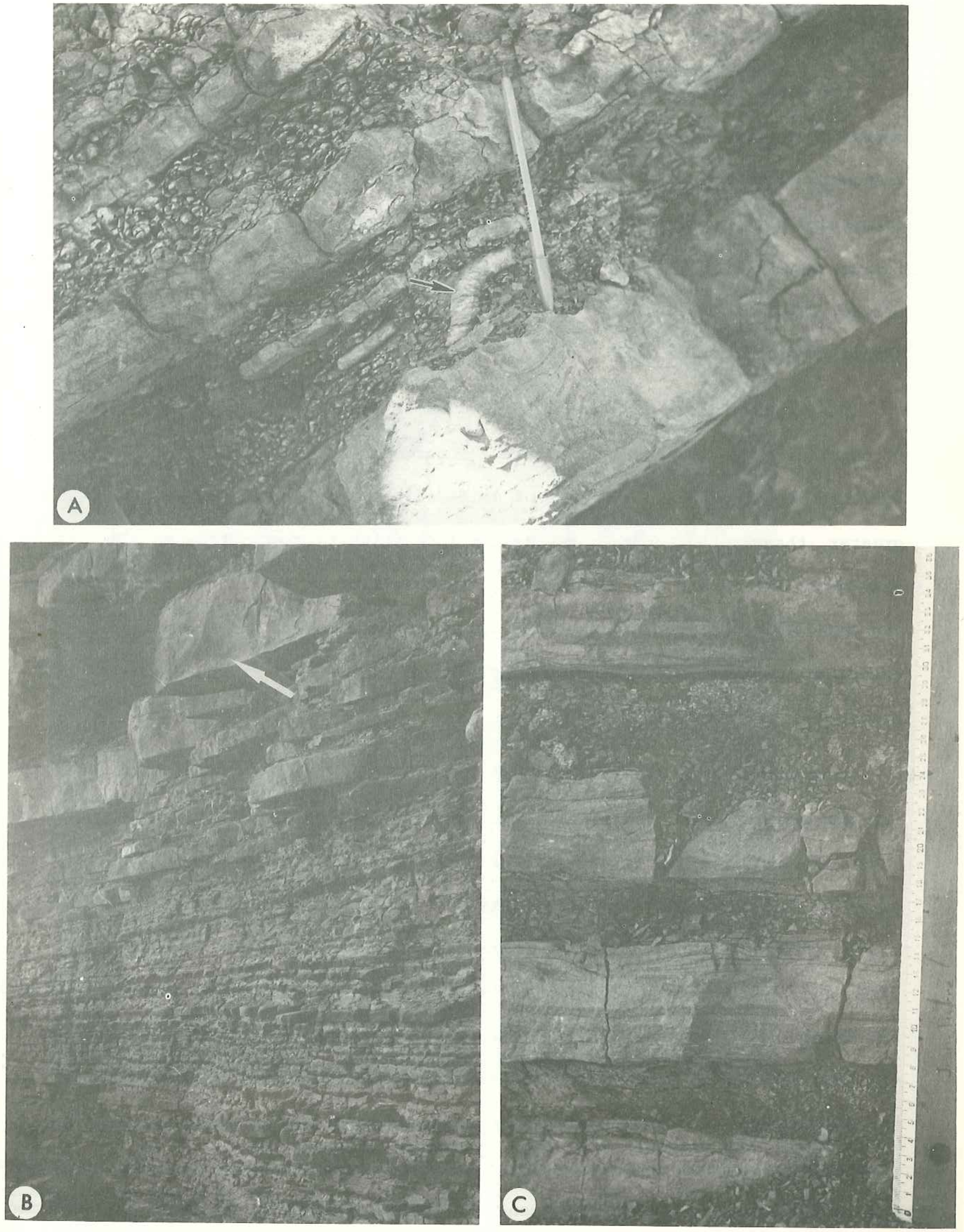


Fig. 33. Intercanyon slope facies consisting of thin turbidites and shale sequences east of Braux (stop 5, Excursion day 3). Note burrow (arrow) in A. Graded bed (arrow) in B shows complete Bouma sequence. Incomplete turbidites in C.

Fan and Base-of-Slope Sequences in the Lac d'Allos Region

The Annot Sandstone in certain sectors of the Lac d'Allos-Col de la Cayolle region (Excursion day 4; Fig. 10) present facies associations attributed to transport processes that prevail in proximal base-of-slope environments. The formations display high sand:shale ratios ranging from 4.0 to 8.0 (Fig. 37) and include some particularly thick, coarse sandstone and pebbly sandstone units between important sections of well-stratified, fine to medium grade sandstone turbidite-shale cycles (Figs. 14 B, 34).

The proportion of chaotic slump and pebbly mud strata (Figs. 36 A) and of conglomerate units (generally of the disorganized type; Fig. 36 B) is somewhat less important, and that of well-defined turbidites (Fig. 34 B) is greater, than at the Annot-Contes-Menton localities to the south. Maps depicting sand:shale ratios and the percentages of pebble-rich strata in the region between the Lac d'Allos and the Argentera-Mercantour Massif reveal two major lobes extending in a westward direction (Fig. 37). Paleocurrent trends digitate within these lobes (top, Fig. 37).

Examples of very thick (3 to over 10 m, or more) sandstones in this locality include those forming the Tours du Lac along the southern part of the Lac d'Allos (Fig. 34 A). These are interpreted as the coarse fills of channels, i.e., probably inner (or suprafan) fan-valleys as defined in various submarine fan models (Figs. 15, 39, 40) and are comparable to those mapped in modern oceans (Fig. 40 A). The poorly graded massive strata represent sandflow (grain/fluidized) and debris flow deposits. Many of these are composite, amalgamated units, and the base of some of these thick sequences truncate underlying finer sequences (arrow, Fig. 35 A). Shale clasts abound in the sandstone and pebbly sandstone strata (Fig. 35 B, C). The massive beds alternate with thinner sandstone turbidite sheets and occasionally thick sequences of shale (the latter probably includes mud turbidites as well as hemipelagic deposits). These finer grade, well-stratified units, interpreted as interchannel deposits, consist largely of overbank sand and mud flows and possibly levee deposits (cf., Fig. 39).

Fig. 34. Typical sandy flysch (type 2) facies of the Annot Sandstone southwest of the Col de la Cayolle (stop 1, Excursion day 4). A, Tours du Lac d'Allos, south of lake. B, alternating turbidite-shale sequence near Pas de Lausson, east of the Lac d'Allos.

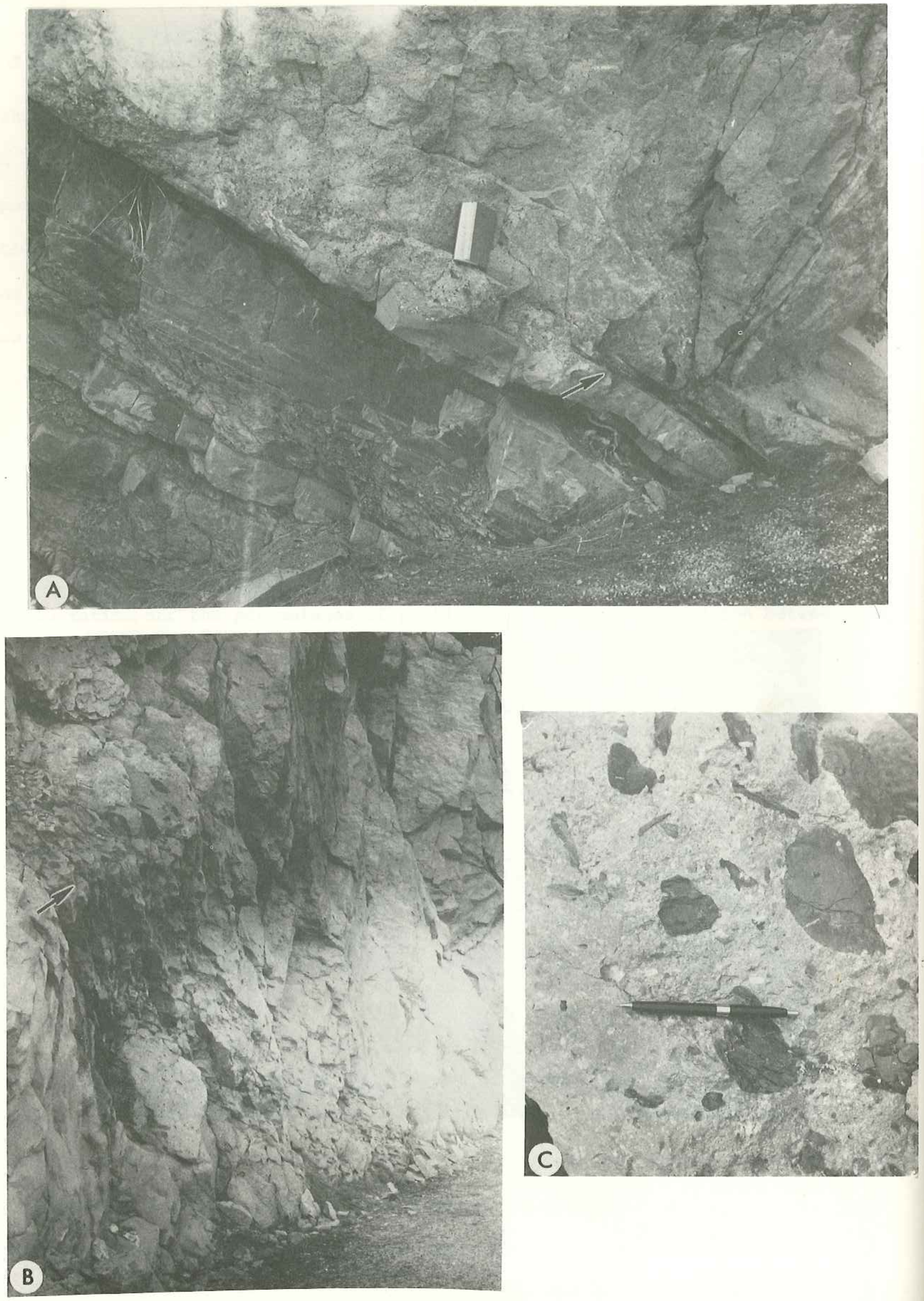


Fig. 35. Annot Sandstone near the Col de la Cayolle (stop 2, Excursion day 4). A, irregularly graded pebbly sandstone base of massive bed cuts underlying units (arrow); book = 20 cm; B, 2 m-thick sequence of shale rip-up clasts (arrow) within massive unit. C, close-up view of clasts in coarse pebbly sandstone (debris flow) shown in B; pen = 13 cm.

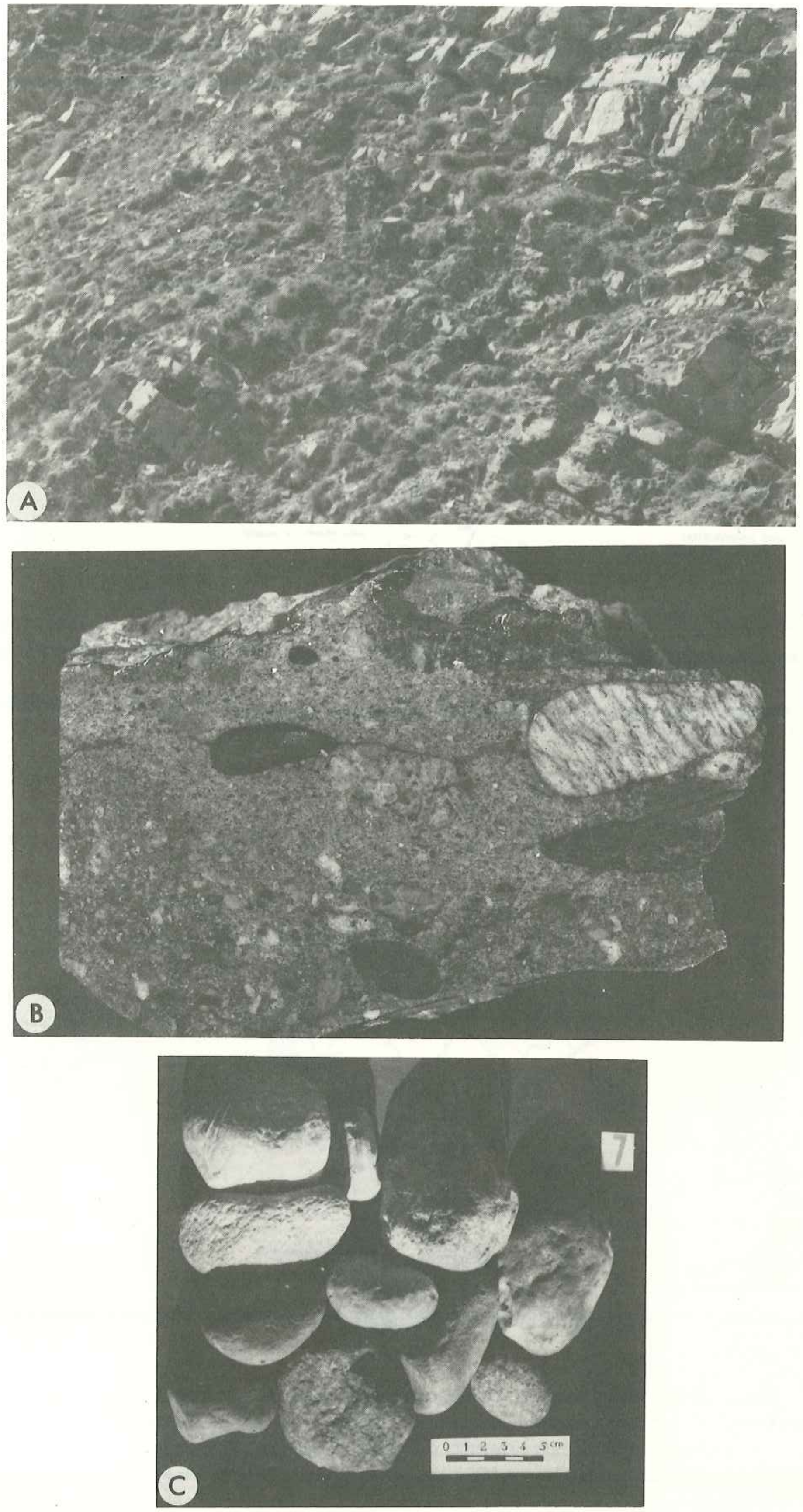
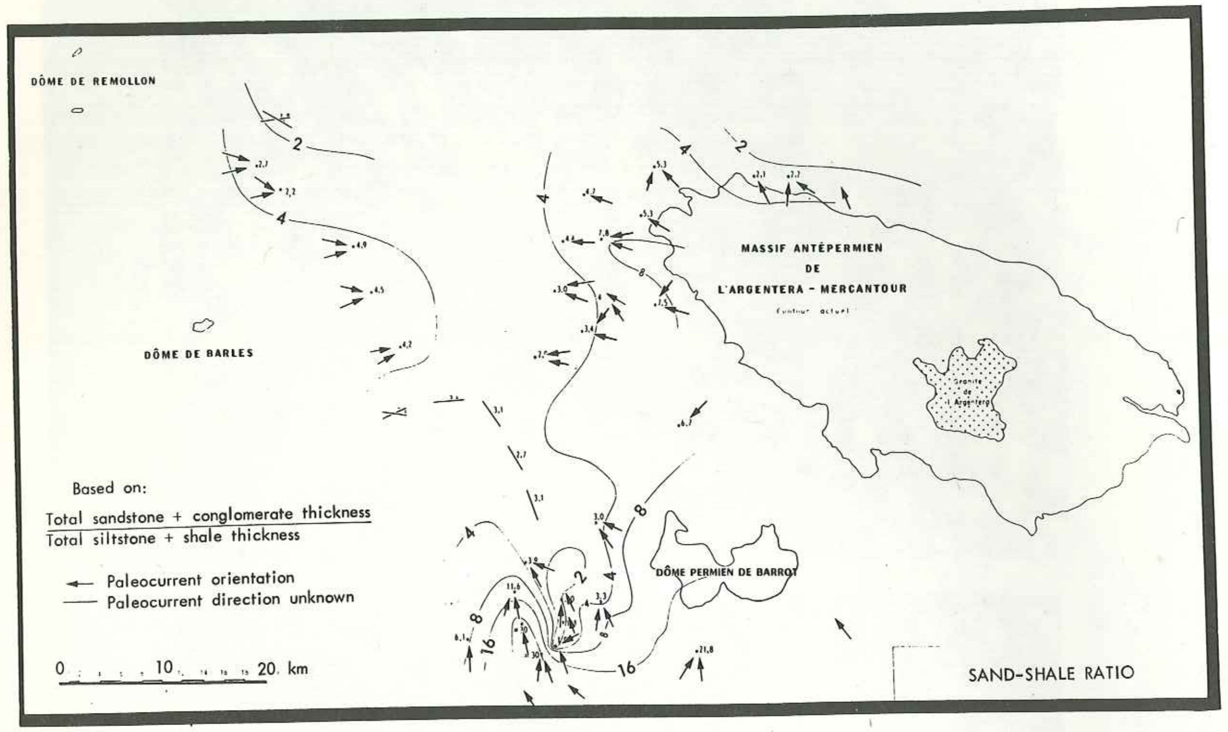


Fig. 36. A, 3 m-thick chaotic unit consisting of pebbly mudstone between sandstone turbidites. B, 10 cm-long slab section of disorganized conglomerate. C, pebbles from pebbly mudstone at the Bec de Marseglia section. All examples are from sections east of the Col de la Cayolle (Excursion day 4).



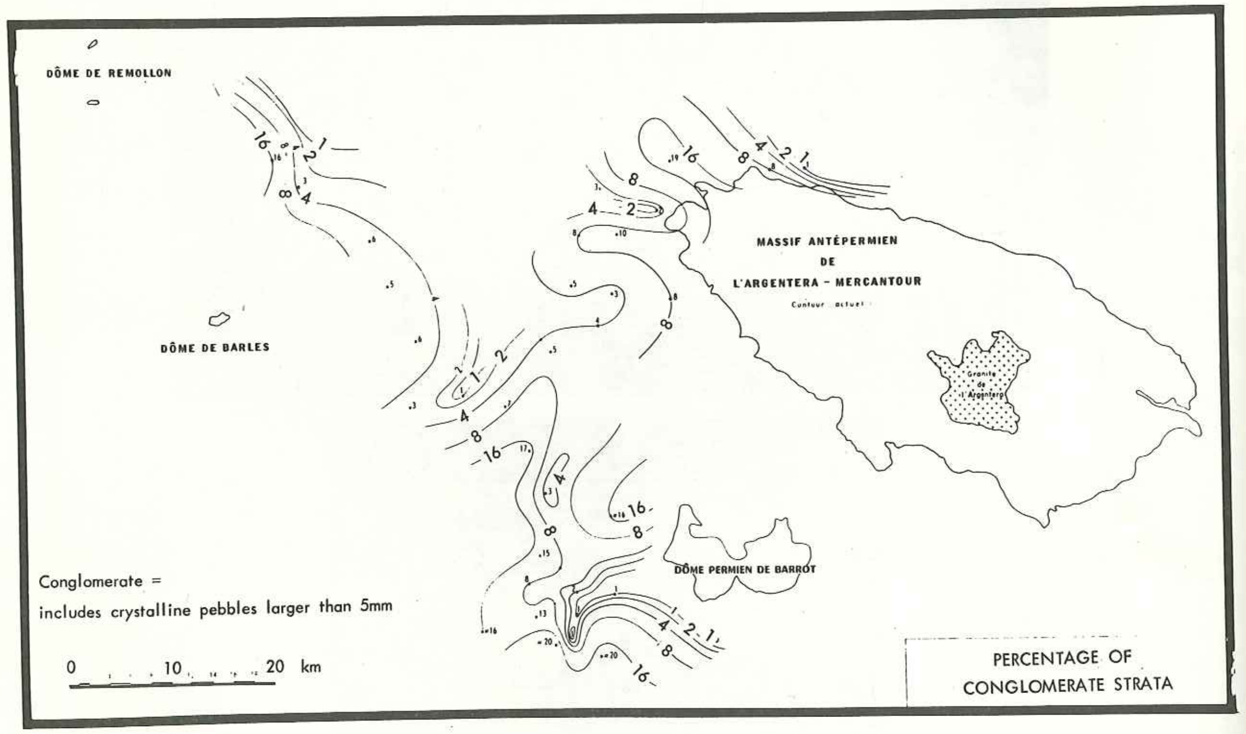


Fig. 37. Maps depicting major paleocurrent trends, sand-shale ratio (upper) and percent of conglomerate strata. Note the lobe-shaped configuration in the Lac d'Allos region northwest of the Argentera-Mercantour Massif (compare with patterns shown in Fig. 40).

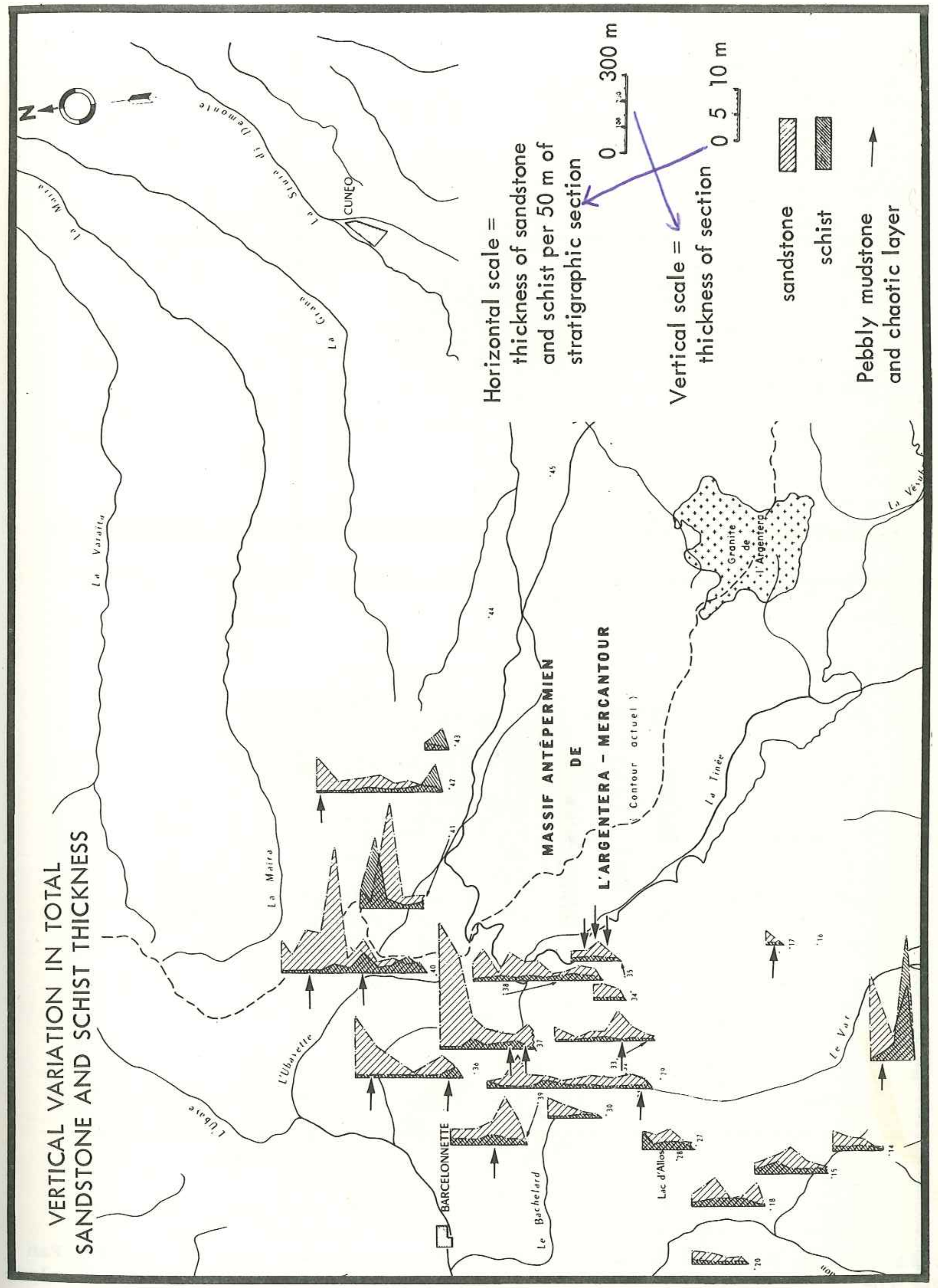
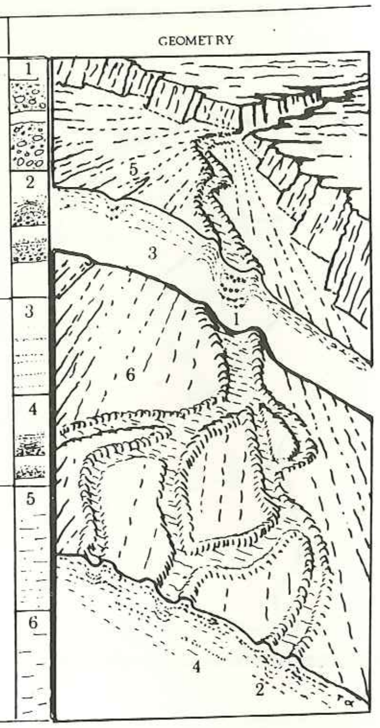


Fig. 38. Vertical and lateral variation of average sandstone and schist thickness (per 50 m of section) in sections mapped in lobe-shaped areas defined in Fig. 37. Arrows show position of pebbly mudstone in each section.

	SIZE	SORTING	COMPOSITION	SEDIMENTARY STRUCTURES	LITHOLOGY
CHANNEL COARSE LAYERS Upper Fan	gravel	very poor	**lithic** wacke sands displaced fauna & detritals	lack of grading and structures	**thick** sandstone and muddy conglomerates with interbedded mudstone
Lower Fan	fine sand	moderate	**arkosic or lithic-arenite or** same as upper channel plus grading of mica, light and heavy minerals, forams **vertically upbed & latterally downchannel**	graded beds cross-bedded laminated cut fill mud clasts	sorted sandstone interbedded with claystone
INTERCHANNEL COARSE LAYERS Upper Fan	fine silt	very poor	high mica & plant fragments	Silt laminae common	mudstone with silt lamina
Lower Fan	fine sand	moderate	same as lower fan channel coarse layers	same as lower fan channel coarse layers	sorted sandstone interbedded with claystone
HEMIPELAGIC LAYERS Upper Fan (near continental slope)	silty clay	very poor	high terriginous & low planktonics **in sand** fraction	worm burrows mottling fecal pellets	mudstone
Lower Fan (seaward of continental slope)	clay	poor	low terriginous & **high** planktonics		claystone



Indicate gradation and magnitude of parameters

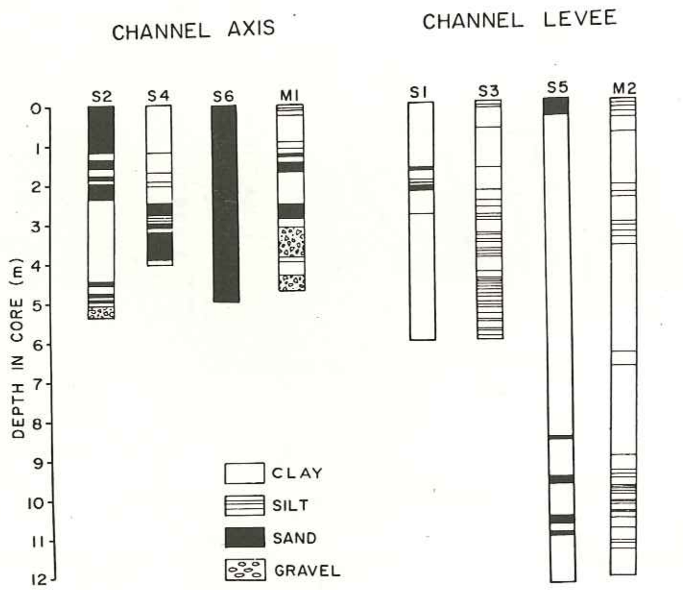


Fig. 39. Upper, model of submarine fan sedimentary facies, based on Astoria Fan off the coast of Oregon (see Fig. 40). Lower, examples of modern base-of-slope channel axis and levee deposits as revealed in cores (after Nelson and Kulm, 1973).

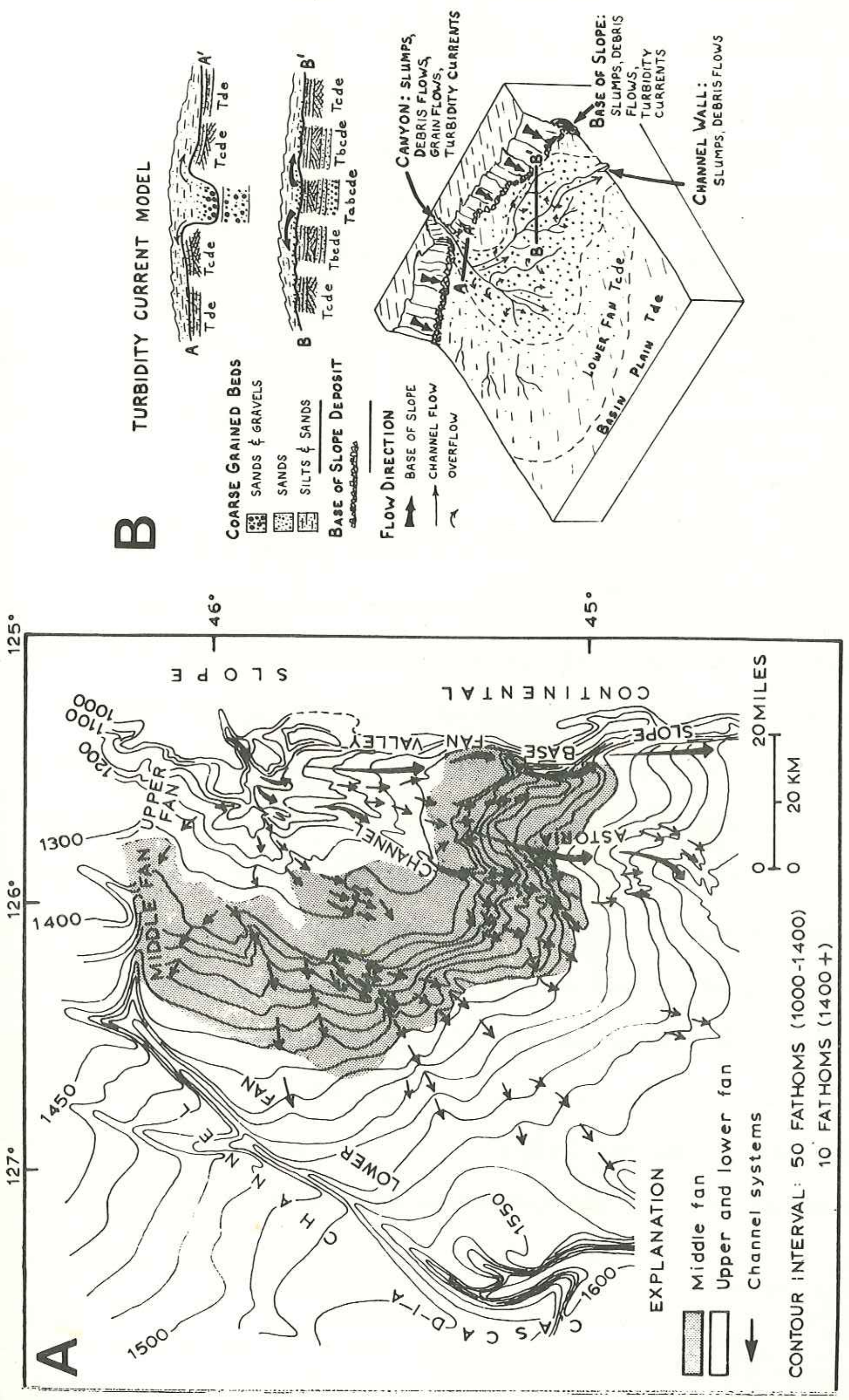


Fig. 40. A, dispersal patterns and radial lobes of Astoria Fan (after Nelson and Nilsen, 1974). B, base-of-slope and submarine fan sedimentation model emphasizing turbidity current processes on fans. Section A-A' shows hypothetical distribution of sediment in a single flow; section B-B' depicts distribution of turbidite structures (after Nelson and Kulm, 1973).

The concentration of pebbly mudstone (Fig. 36 A), chaotic sandstone strata and disorganized conglomerates (Fig. 36 B) together indicate proximality to the zone of decrease in gradient defining the base of the Annot Basin slope. The irregular shape and polymictic nature of pebbles (Fig. 36 C) present attributes generally associated with river gravels which suggests that this coarse material had a fluvial origin and were not subject to much reworking prior to their deposition in the marine environment. These pebbles, along with locally present plant matter, apparently passed rapidly from emerged terrains, through the coastal (possibly deltaic) zone to the deep basin with only minor textural modification in the littoral environment. In sum, the textural composition of pebbles suggest rapid rates of sedimentation as well as a narrow shelf configuration. A possible modern analogue are the pebbles mixed with sand in the Mediterranean basins such as those recovered off the narrow coast of Provence as illustrated by Bourcart (1964; cf., Fig. 24) and Gennesseaux (1966).

The lobe-shaped accumulations within this 20 km by 25 km region northwest of the Mercantour Massif and the associated paleocurrent patterns resemble Astoria Fan sedimentation patterns illustrated by Nelson and Nilsen (1974; cf., Fig. 40). The proportion of fine turbidite sandstone-shale interchannel sequences and coarse fan-valley deposits vary vertically within the same section as well as laterally between sections (Fig. 38). This variation in time and space can best be explained in terms of changes in the position of fan lobes resulting from channel migration in a fan system developing in a closed basin. Thus, the vertical variations in thickness and proportion of sandstone, siltstone and shale in the Lac d'Allos region depicted in Figure 38 record the evolution of upper- to mid-fan lobes as suggested by the fan models in Figures 15, 39, and 40.

Upper to Outer Fan Sequences in the Peïra-Cava Region

The sandstone-shale sequences in the Peïra-Cava syncline (Excursion day 2) are far less well-exposed than those described above. They are easily accessible, however, and present the advantage of displaying a complete sequence of proximal (inner or suprafan) to mid- and outer-fan facies within a relatively short

distance. The syncline (about 14 km from south to north) is, fortunately, oriented roughly parallel to the major paleocurrent trends (Fig. 41) which allows a good evaluation of facies in terms of proximality and transport processes.

As in the case of the Lac d'Allos region, sandstone turbidites dominate the various sections, but other strata types account for a varying proportion of the stratigraphic sections. For instance, a thick chaotic slump unit, covered by a massive sandstone (sandflow, debris flow) sequence (Fig. 42 A), is exposed in one of the southernmost localities (stop 5, above Col St. Roch). This type of chaotic-massive facies would most likely be encountered in the upper (inner) fan environment at the base of the slope [cf., models of Nelson and Kulm (1973), Mutti (1974), Nelson and Nilsen (1974), and others (Figs. 39, 40, 46)]. Massive pebbly sandstones and coarse sandstones include both of the organized and disorganized conglomerate type (cf., Walker and Mutti, 1973). In the case of the former, the base is often conglomeratic and sometimes graded (Fig. 43 A) or reverse graded (Fig. 43 B). More often, however, no fabric or structures are observed in conglomerates at stops 1, 4 and 5 (Fig. 43 C). The latter disorganized conglomerates (cf., Walker and Mutti, 1973) are frequently associated with slump or chaotic structures in the lower part of the unit (Fig. 42 B), or below the base of the bed (Figs. 42 C). The base of these coarse units often display large load structures and other forms of soft sediment deformation (Figs. 44, 45 A). Lamination is occasionally displayed within massive beds (Fig. 45 B); dish structures are more rarely observed. The above coarse and generally massive units in the southern part of the syncline are interpreted as inner-fan (suprafan) channel deposits; the finer, better stratified turbidite-shale sequences between them are probable overbank deposits. The stratigraphic section between the Col de l'Orme and La Cabanette cut by the road (Figs. 46, 47) has been detailed by Bouma (1962) and Lanteaume et al. (1967). These authors have paid particular attention to sedimentary structures associated with turbidites and associated strata types, and the interested reader is referred to the excellent collection of illustrations presented in their publications.

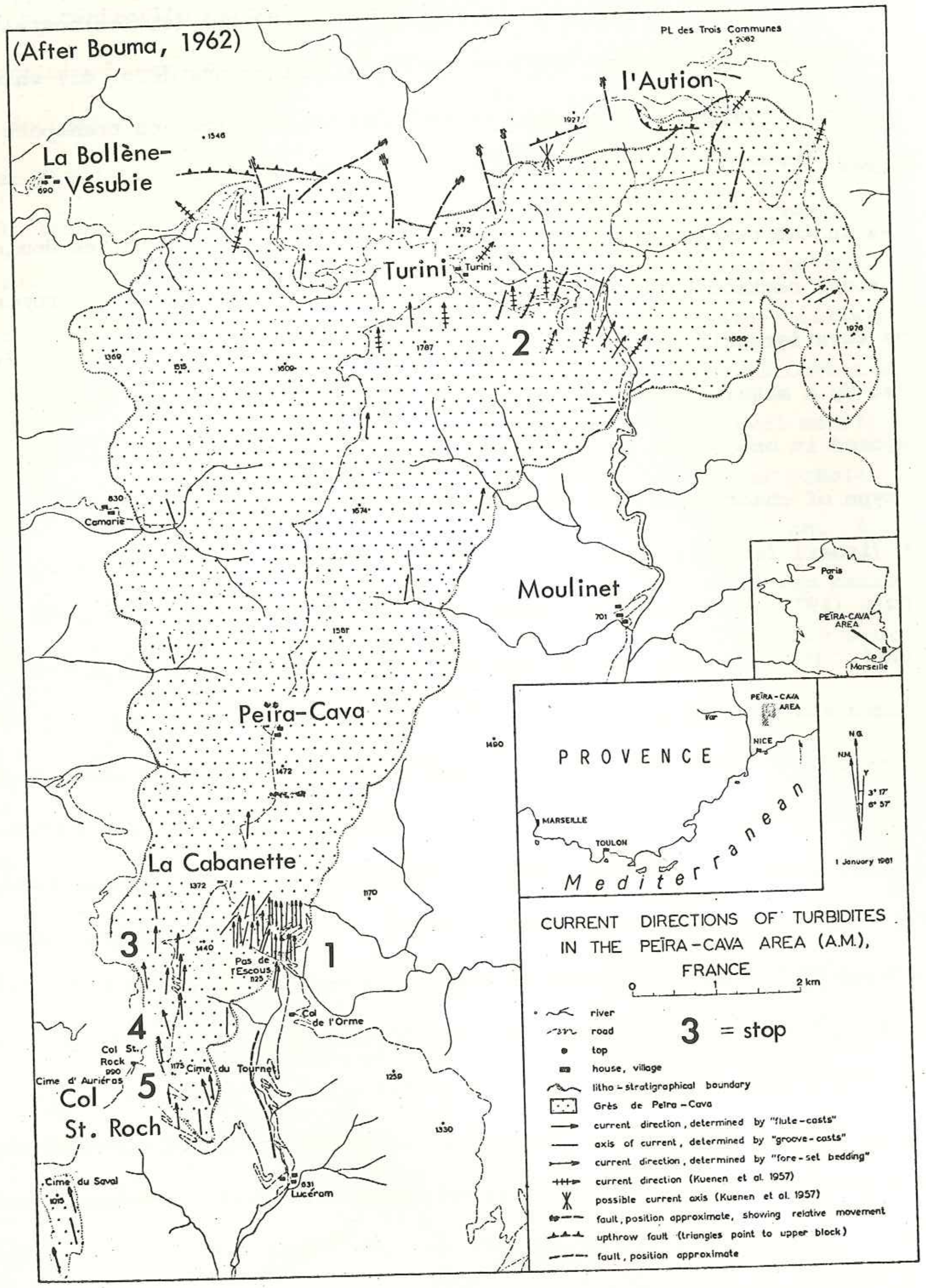


Fig. 41. Map showing sandstone localities examined and paleocurrent directions measured in the Peïra-Cava region (Excursion day 2; see also Fig. 12). Note radial current trends in northern region (after Bouma, 1962).

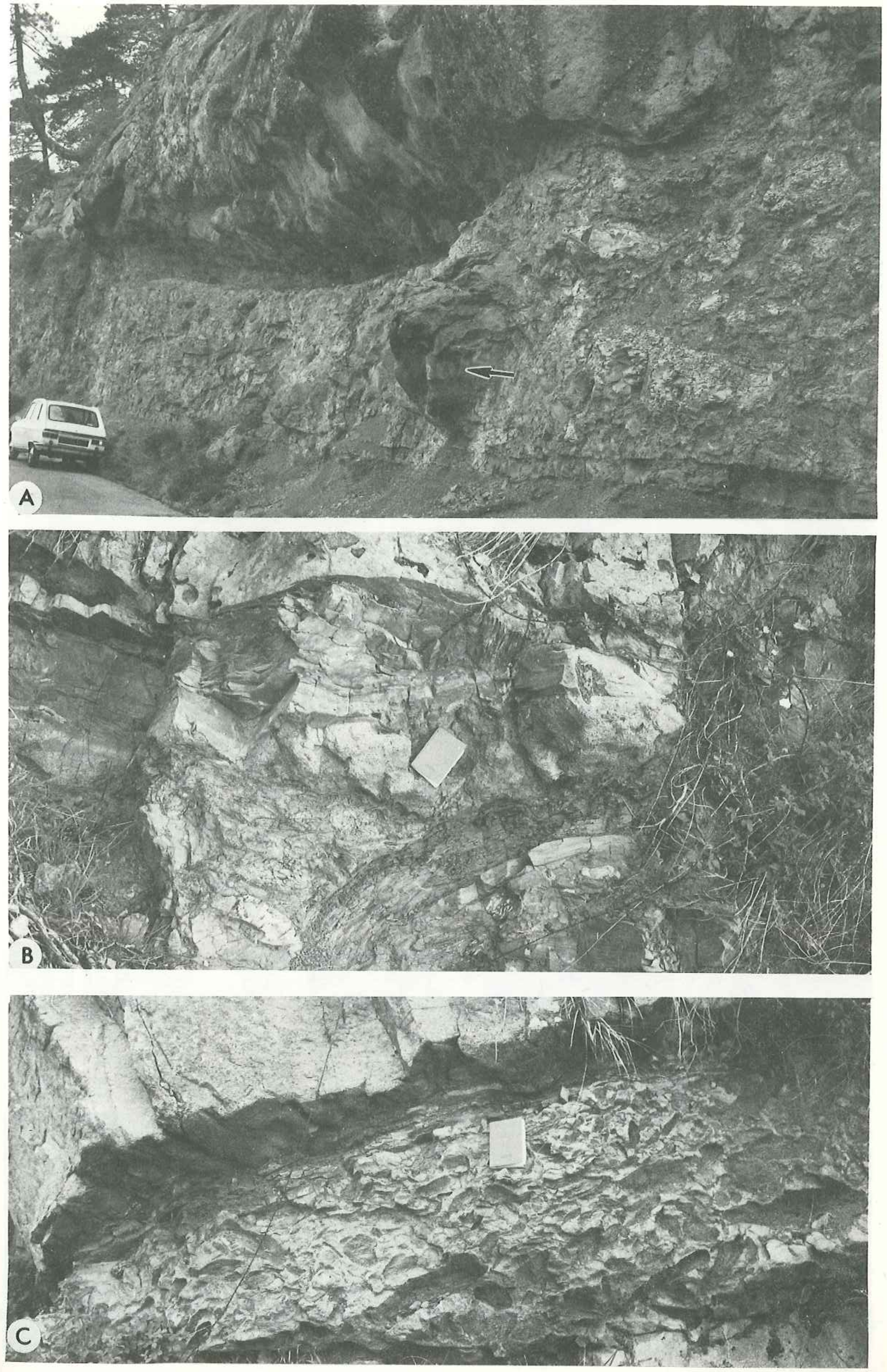


Fig. 42. A, thick chaotic slump unit below massive sandstone in southern part (inner fan) sector of the Peïra-Cava syncline (stop 5, Excursion day 2); note large size of block (arrow). B, chaotic stratification at base of coarse sandstone (stop 1). C, shale rip-up clasts in coarse sand (debris flow) between pebbly sand units. Book = 20 cm.

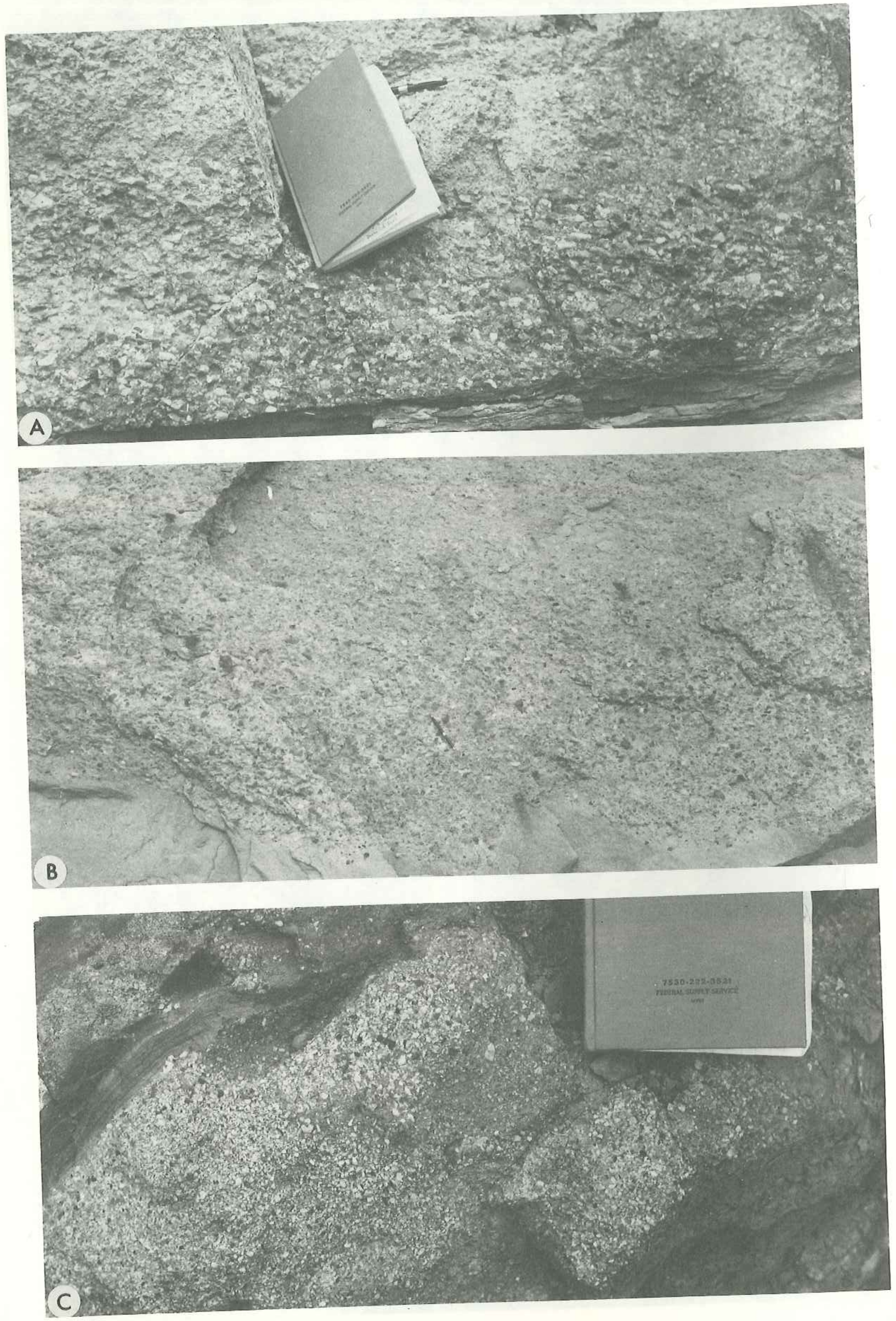


Fig. 43. Examples of different conglomerate types in the Peïra-Cava region (stops 1 and 2, Excursion day 2). A, poorly graded; B, reverse graded; C, disorganized conglomerate (debris flow). Book = 20 cm; pen in B = 13 cm.

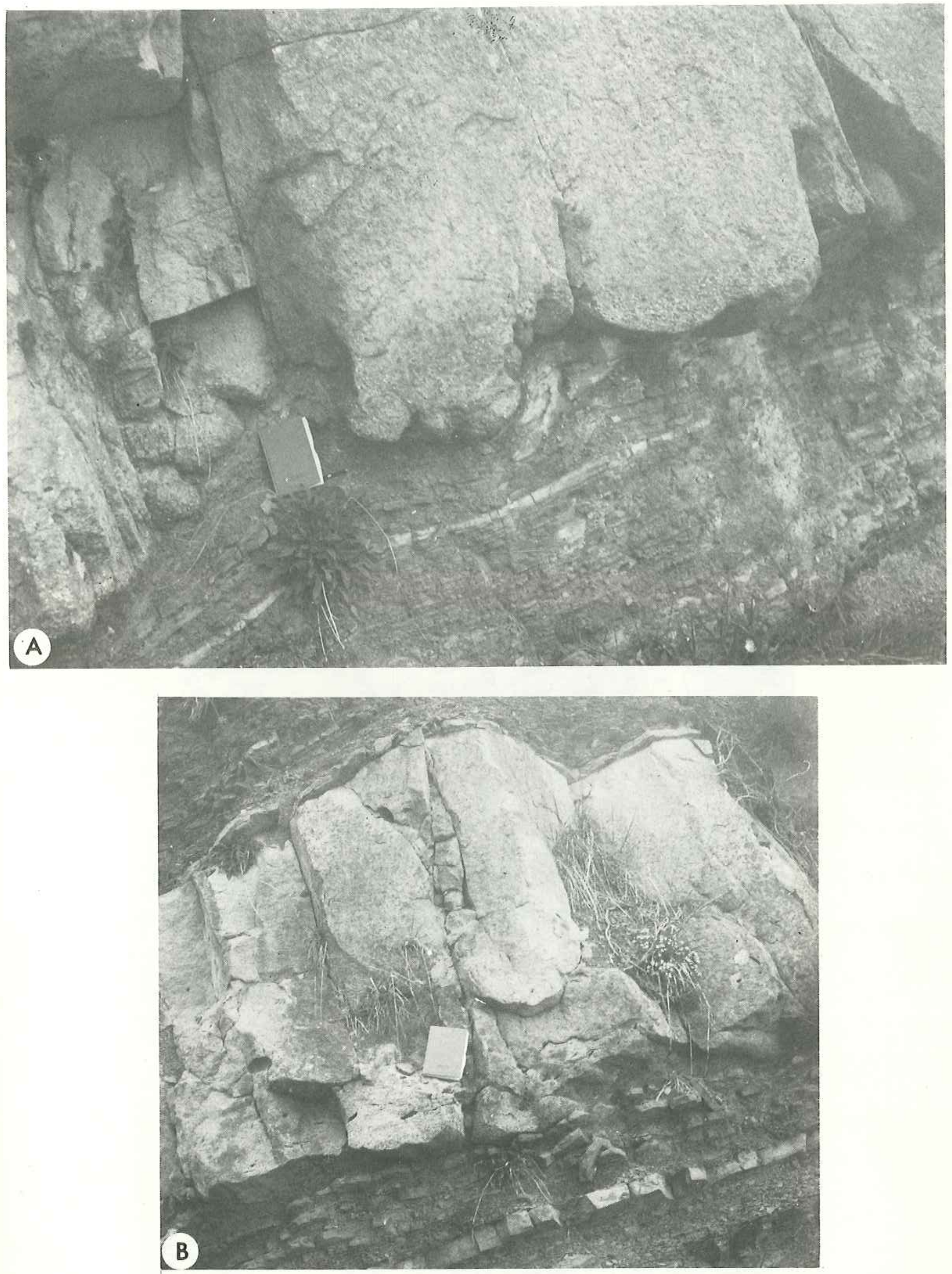


Fig. 44. Large load structures at the base of pebbly sandstone units and soft-sediment deformation into underlying thin turbidite-shale sequences in the Peïra-Cava area (Excursion day 2). Note concentration of pebbles at base of bed in A, and rip-up clasts in B. Book = 20 cm.

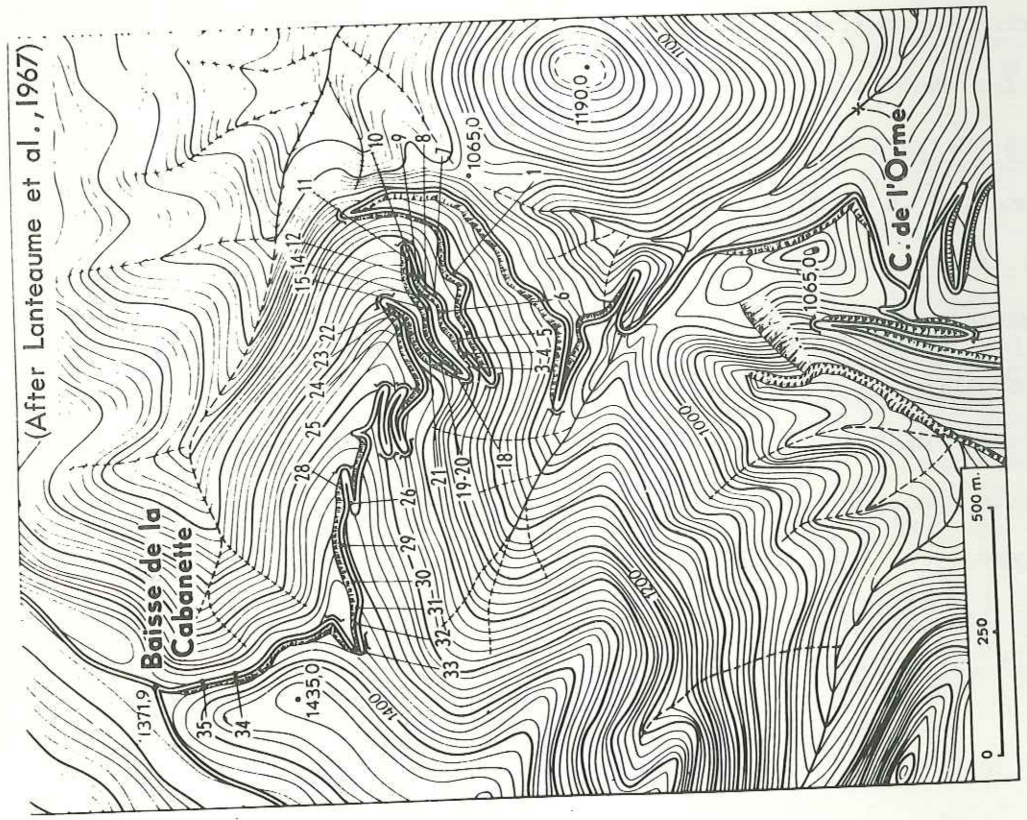
Fig. 45. A, massive sandstone unit, possible fan-valley channel deposit, cut into underlying shale sequence. B, laminated section of a massive sandstone bed. Peïra-Cava region (Excursion day 2). Book = 20 cm.

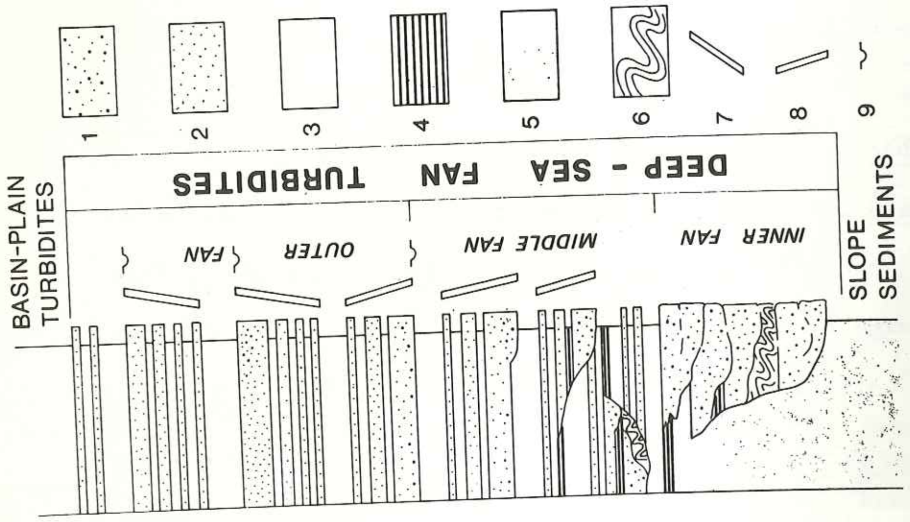
Mid-fan to more distal outer-fan sequences are observed further to the north in the Peïra-Cava syncline. Here the proportion of shale and somewhat thinner turbidite sheets increase (lower sand:shale ratio than to the south) with somewhat fewer and less thick coarse, massive sandflow and debris flow deposits (Fig. 48). The pebbly sandstones, as in the more proximal fan-valley channels described above, also contain conglomerates at their base. Here, however, a somewhat higher proportion of graded (organized conglomerate) units are observed and these are less frequently associated with chaotic bedding at their base. The lower part of the section between the Col de Turini and Moulinet (stop 2) begins with a fine flysch sequence consisting of thin turbidite sheets alternating with shale; this may represent an outer fan facies (cf., model in Fig. 46).

The stratigraphic section here, as in the Lac d'Allos region, at times becomes sand-rich and coarser vertically. The time-spatial lithofacies changes recording the fan evolution, are closely influenced by the migration of channels and overbank deposition. The progressive change in paleocurrent orientation observed as one climbs the section and travels westward along the road (Fig. 41) tends to support this changing trend of channel migration and overbank deposition which characterizes submarine fans, particularly the mid- to outer-fan environments. A section including thin, finer grade turbidites (b-c-d, c-d Bouma divisions) and shale sequences exposed in the northern part of the Peïra-Cava syncline north of the Col de Turini (Fig. 14 C) may represent more distal fan facies. Here the effects of channelization appear less marked, and the role of sand and mud turbidite sheet flows and hemipelagic deposition are clearly more important.

TRANSPORT PROCESSES IN ANNOT BASIN SLOPE ENVIRONMENTS

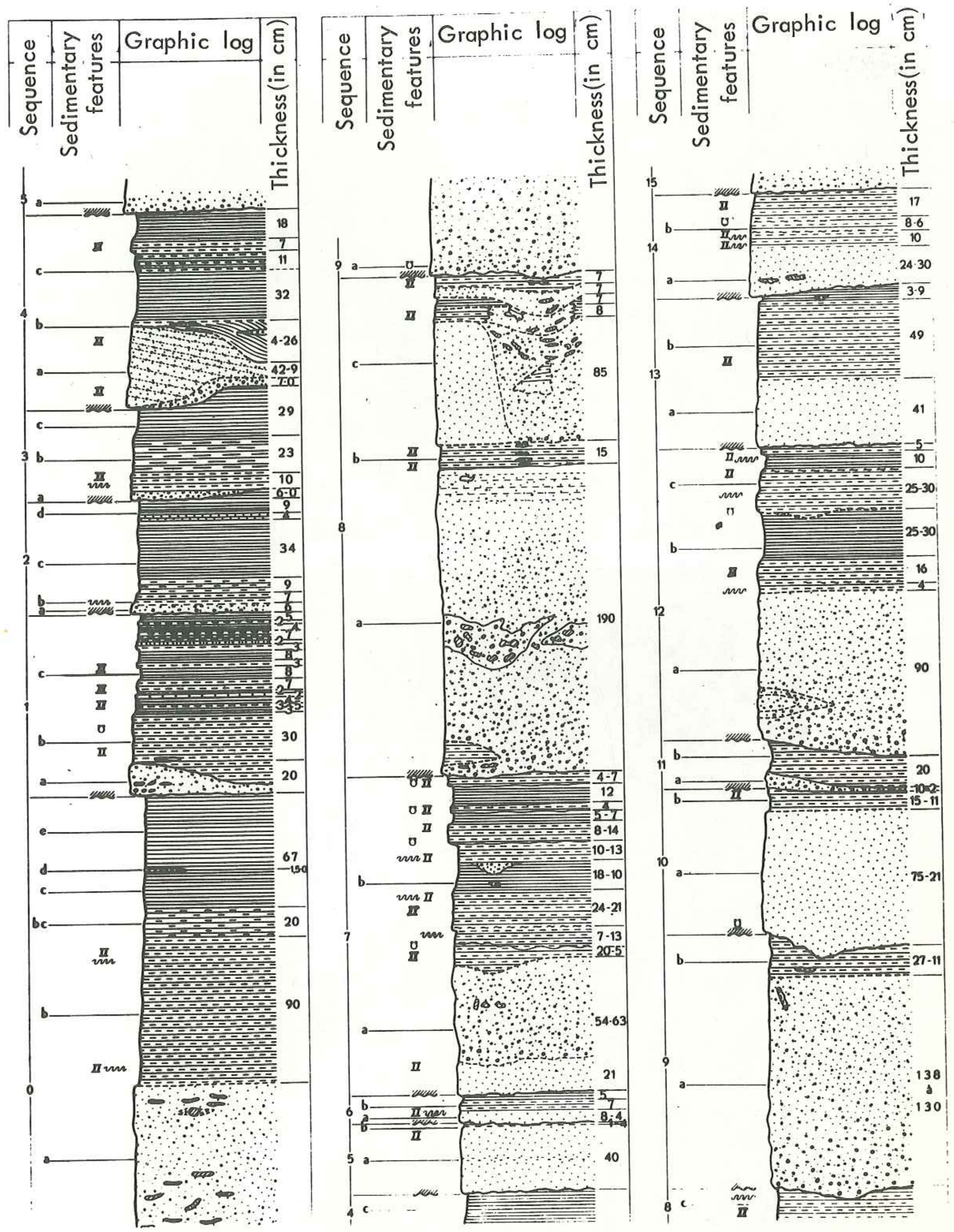
Most of the earlier sedimentological surveys of the Annot Sandstone (Kuenen et al., 1957; Stanley, 1961, 1963; Bouma, 1962; Lanteaume et al., 1967) emphasized transport processes related to the deposition of type 2 facies described as flysch. These studies focused on the role of turbidity currents





1, thick-bedded graded and (or) crudely laminated coarse-grained sandstone and conglomerate; 2, thick-bedded graded sandstone and varying amounts of finer grained current-laminated deposits, including mudstone; 3, mudstone and parallel bedded, thoroughly current-laminated sandstone and siltstone; 4, thin, lenticular, and discontinuous beds of fine- to coarse-grained sandstone exhibiting grading and poorly developed current laminae; 5, so-called "hemipelagic" mudstone; 6, chaotic sediments; 7, thickening upward cycle; 8, thinning upward cycle; 9, shallow channels

Fig. 46. Left, road between the Col de l'Orme and la Cabanette in the Peïra-Cava region (stop 1, Excursion day 2; Figs. 12, 41) showing location of units in graphic log in Fig. 47 (after Lanteaume et al., 1967). Right, hypothetical vertical submarine fan sequence (after Mutti, 1974).



(After Lanteaume et al.,1967)

Fig. 47. Graphic log showing lower part of the section observed between Col de l'Orme and Baisse de la Cabanette in the Peïra-Cava region (stop 1, Excursion day 2). Location of sequences is shown in Fig. 46 (after Lanteaume et al., 1967). Note large proportion of poorly, or non-graded, massive pebbly sandstone and chaotic units between shales and thinner turbidites. The thicker units are interpreted as upper fan-valley channels; the finer are overbank interchannel deposits.

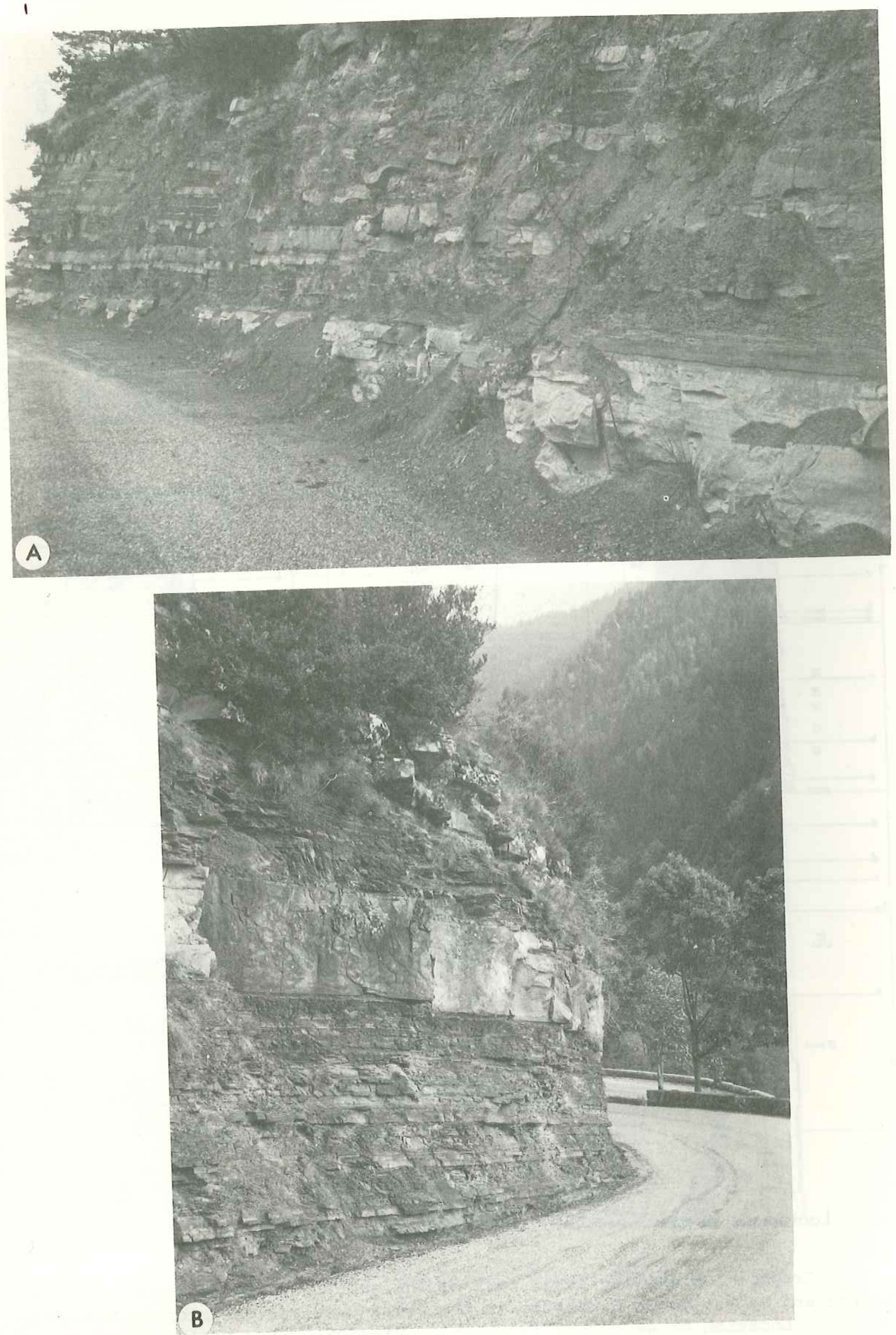


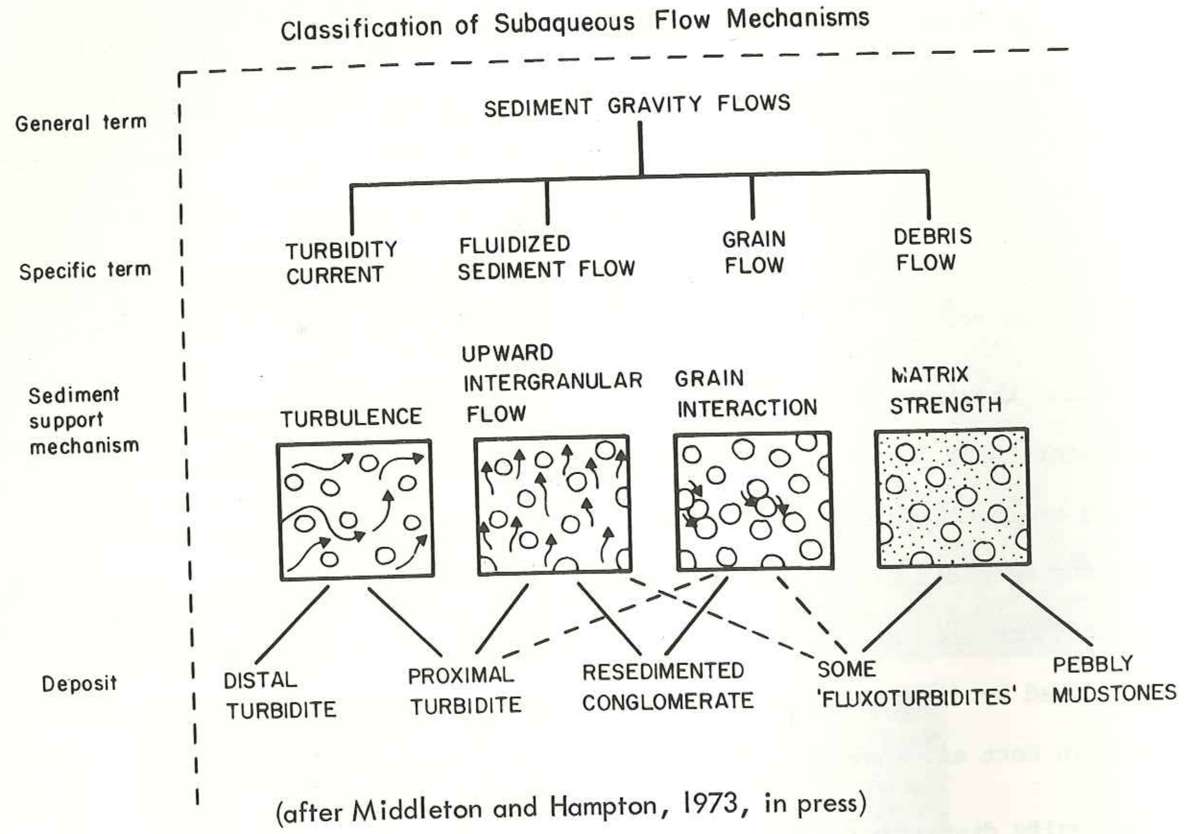
Fig. 48. Type 2 facies showing a higher proportion of shale between thinner turbidites in Peïra-Cava area (Excursion day 2). Sequences such as this are more distal (mid- to outer-fan) than those shown in Figs. 32, 45 and 47.

in the emplacement of the sandstone and pebbly sandstone deposits, particularly graded ones, in this formation. The finer-grade siltstones and shales were attributed a rain-of-sediment pelagic origin while the chaotic and poorly stratified sand-mud mixes were recognized as slump masses. As our investigations of this formation have progressed it has become apparent that a more complex set of transport mechanisms were involved in the deposition of the different facies recognized.

During the past 10 years, much attention has been paid to the mechanics of sediment transport in fluids, and considerable advances have been made by relating sedimentary features preserved in the rock record to experimentally produced structures in the laboratory (cf., Bagnold, 1956; Dott, 1963; Middleton, 1965; and others). These theoretical and experimental studies are being supplemented by direct observations made in modern continental margins (cf., reviews in Dott and Shaver, 1974; and Kelling and Stanley, in press).

Deposits displaying internally deformed structures, herein termed chaotic units, are related to gravity-triggered slumping mechanisms. It was noted earlier that an important proportion of chaotic sandstones, mudstones — and mixes thereof — comprise the canyon wall and canyon axes facies at the Annot, Contes and Menton localities and the base-of-slope environments including proximal fan channels in the Lac d'Allos and Peïra-Cava regions (Fig. 42). Slumps can be triggered by earthquake tremors, although this is not an essential requirement; rapid sedimentation alone (such as off a delta) can result in sediment displacement on a slope by underconsolidation of muds, changes in excess pore fluid pressure and spontaneous liquefaction. A flood carrying a large volume of sediment across a narrow shelf onto the slope, or even a period of intensified burrowing by benthic organisms (Stanley, 1970), might be sufficient to initiate the downslope movement of metastable sediment.

In this respect, it should be recalled that the structural setting of the region in which the Annot Sandstone formation accumulated was a very mobile one. Sediments were transferred rapidly from emerging terrains, some of considerable



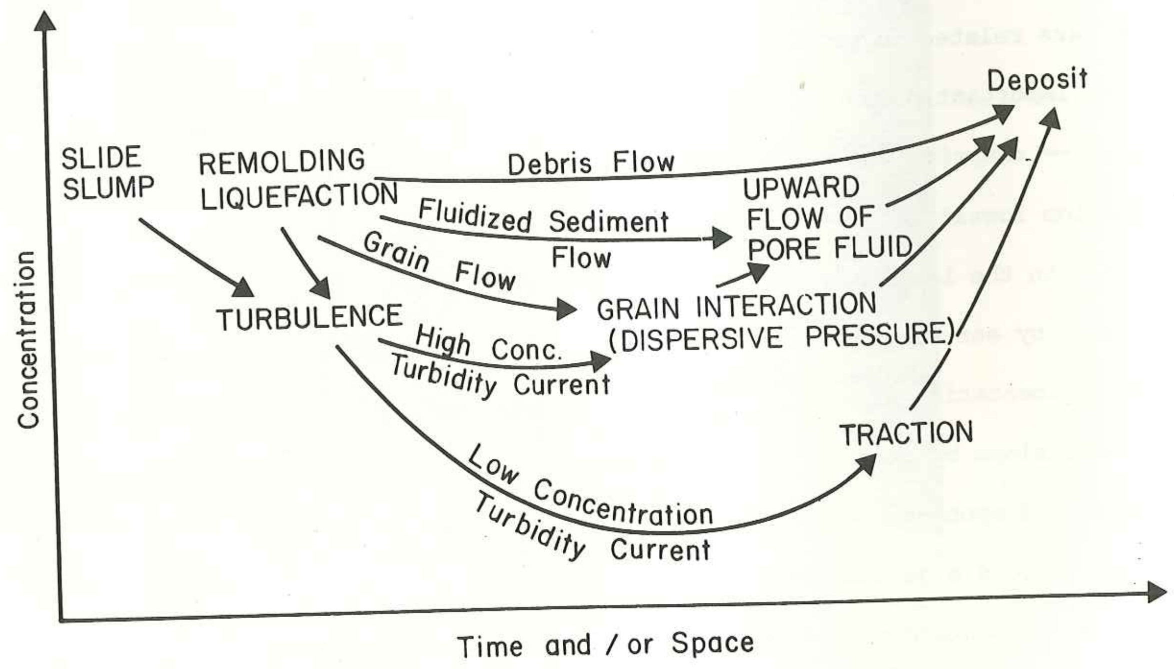


Fig. 49. Upper, classification of subaqueous gravity flows (turbidity current and fluidized, grain and debris flows) based on sediment support mechanisms. Lower, evolution (hypothetical) of a single flow in time or space (after Middleton and Hampton, 1973, in press).

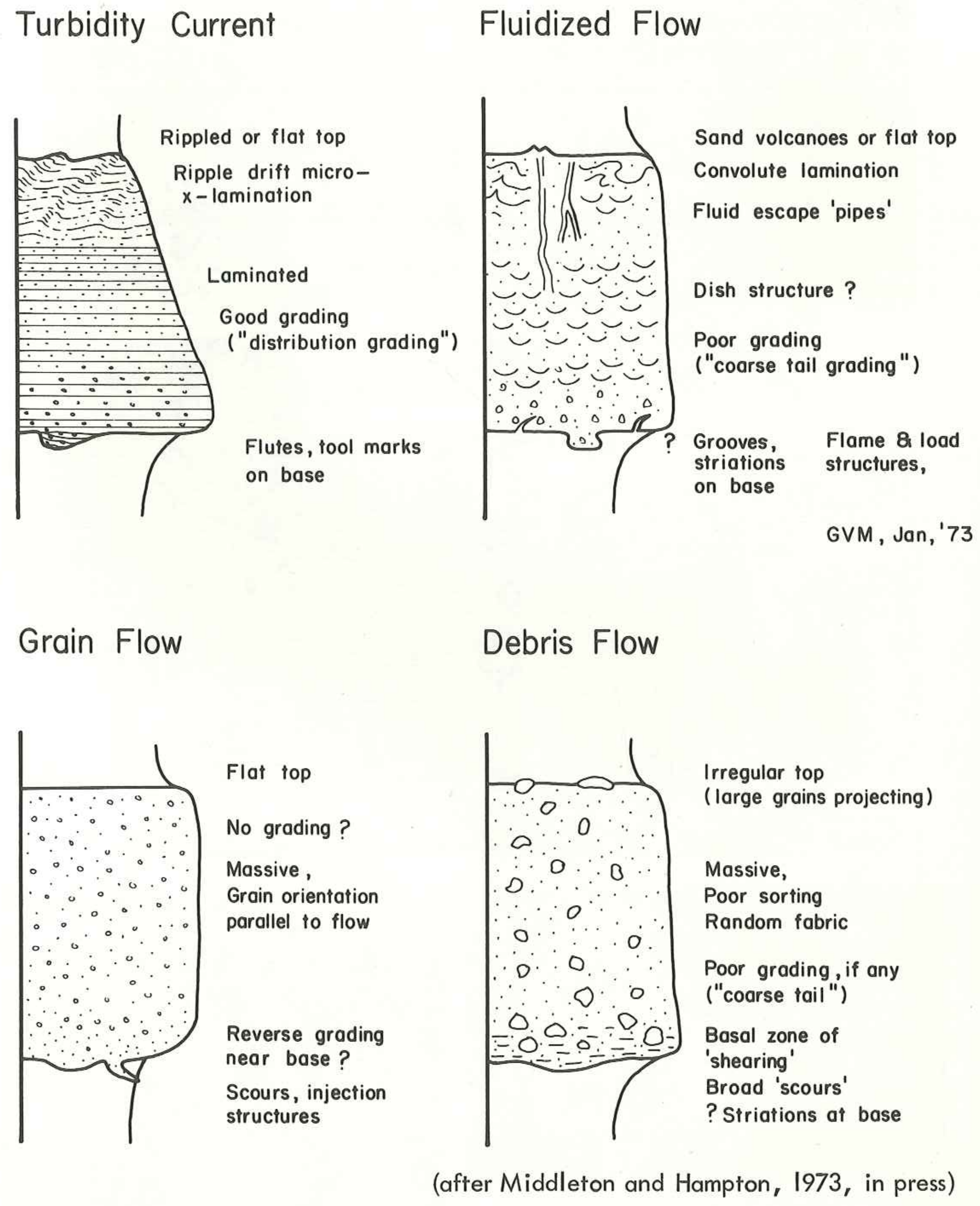


Fig. 50. Sedimentary structures in turbidity current and fluidized, grain and debris flow deposits. These sequences of structures are attributed to hypothetical single-mechanism flows (after Middleton and Hampton, 1973, in press).

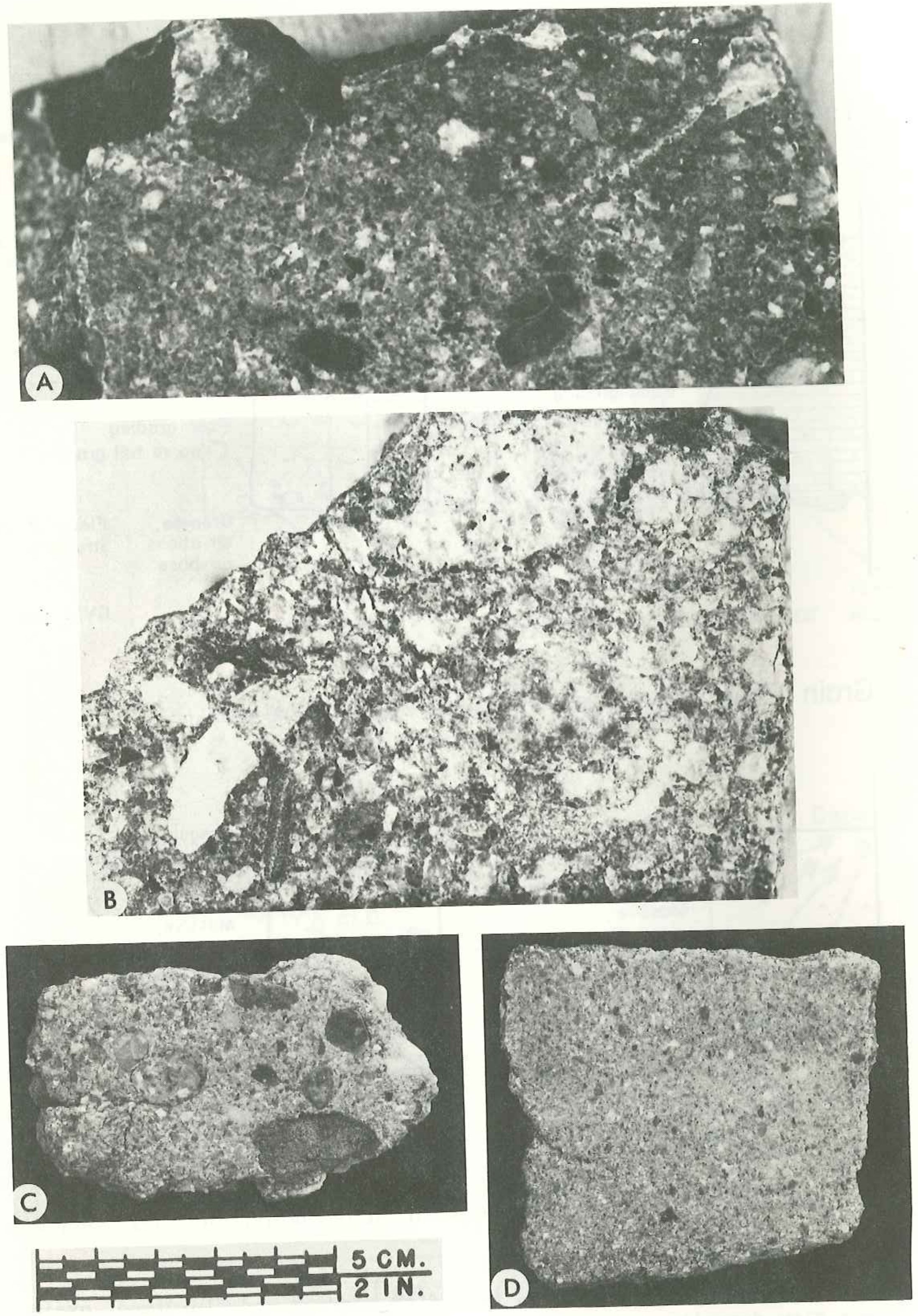


Fig. 51. Slabed sections of conglomerates (disorganized) in sandy debris flow deposits from the Lac d'Allos-Col de la Cayolle (A, B) and Annot (C) regions. D, pebbly sandstone type typical of massive Annot, Contes and Menton sandflow deposits. Compare with Figs. 19 A, 20 D, and 43 C.

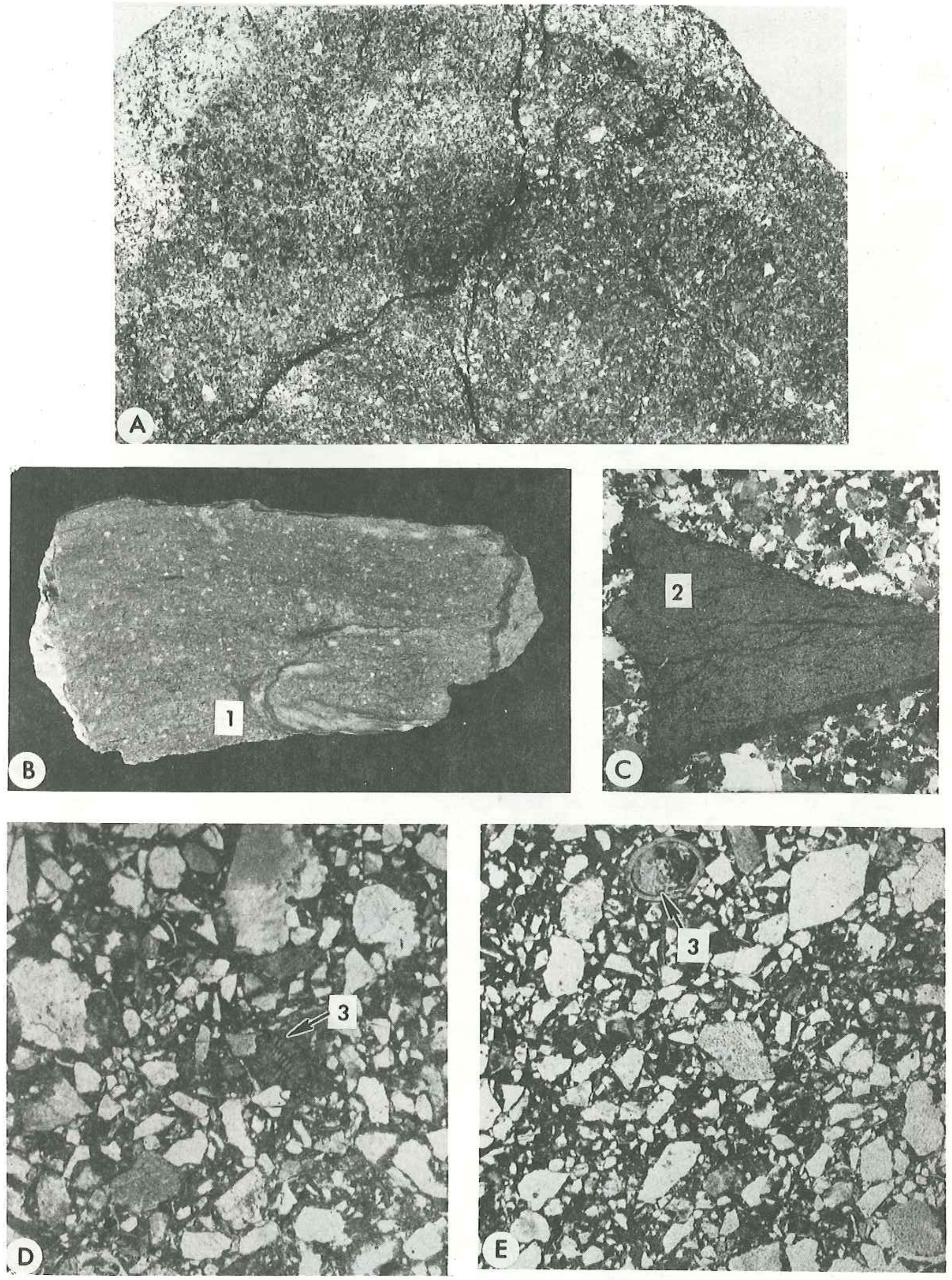


Fig. 52. Slabed rock sections (A, B, 8 and 10 cm long, respectively) and thin sections (C-E) of pebbly sandy mudstone types from the Lac d'Allos-Col de la Cayolle region. Note contorted laminae, 1; rip-up shale clast, 2, and reworked fauna, 3. Compare with Figs. 20 B, 35, 36, and 42.

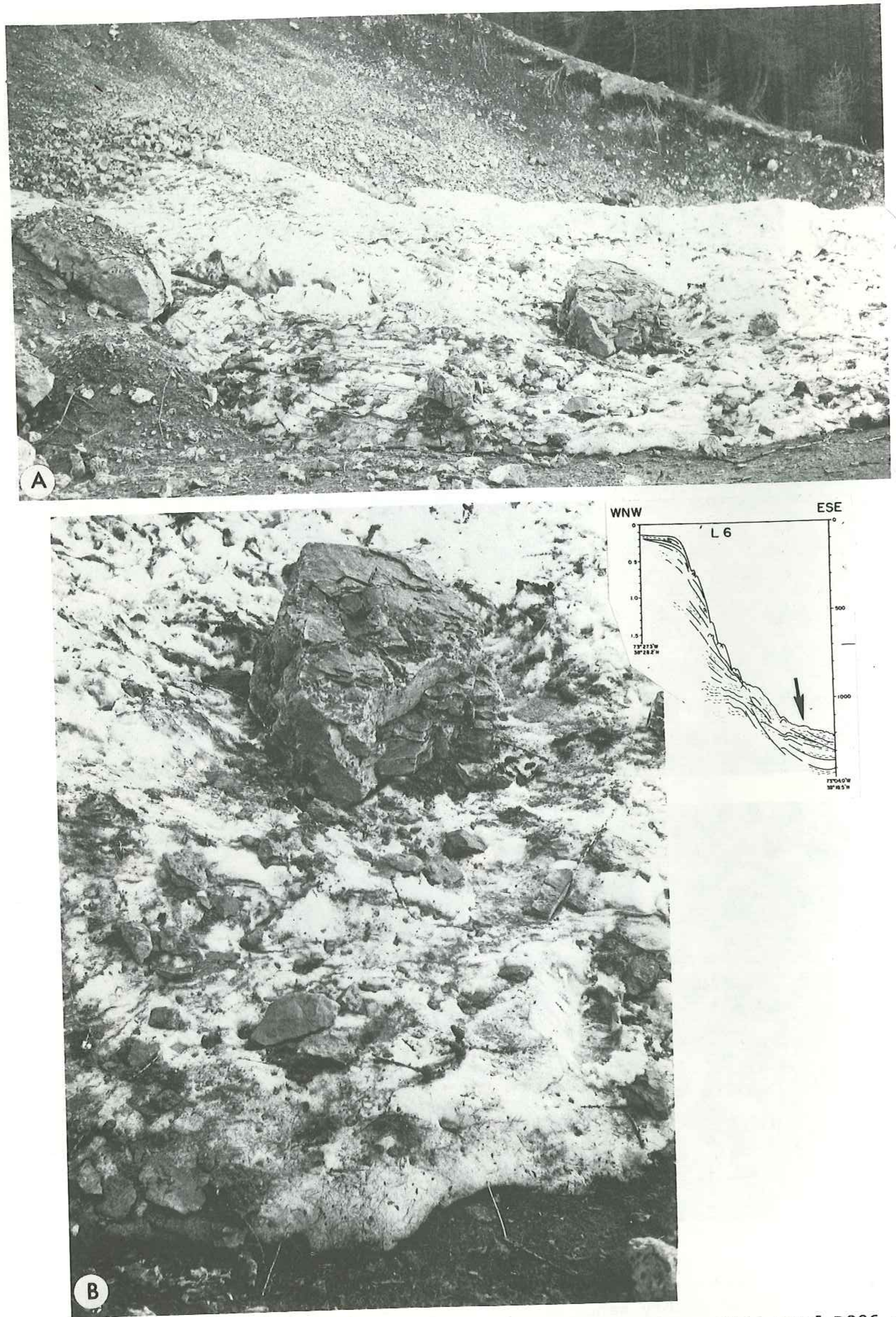


Fig. 53. Example of snow avalanche observed in May 1975 on small road D226 north of the Lac d'Allos. Note blocks of varying sizes supported by snow matrix; compare with debris flow deposits in Figs. 36 and 42. These deposits appear analogous to chaotic units mapped in modern base-of-slope environments (cf., arrow in inset off U. S. Atlantic margin, Kelling and Stanley, 1970).

relief, into a basin undergoing considerable change at the beginning of the Oligocene. The essential conditions necessary to produce frequent slumps were available: structural displacement and rapid sedimentation rates. The concentration of slump units we have described help define those sectors where paleoslope gradients may have been most important. As we have shown in this investigation, slump deposits are concentrated in canyon heads and axes, on the walls of canyons and fan-valley channels, and at the base of the Annot Basin paleoslopes.

Recent re-examination of the sandstone exposures at Annot, Contes and Menton indicates that at least two-thirds of the massive beds are non-graded and do not show the typical turbidite structures. The fused or amalgamated nature of the strata and the very low number and thickness of mud interbeds reflects the high frequency of downslope sand transport episodes. Mud deposited by suspension had little time to accumulate between successive flows which carried sand and pebbles into the submarine valleys. The association of sedimentary structures at the three paleochannel localities indicate that several types of gravity flow processes were responsible for the emplacement of sands. A natural continuum of sediment gravity flows, a term applied to sediment-fluid mixtures under the action of gravity, has been described by Middleton and Hampton (1973, in press). The gravity flow mechanisms are classified according to the dominant sediment-support mechanisms involved and are defined as follows by Middleton and Hampton (1973, p. 2):

> (i) *turbidity currents*, in which the sediment is supported mainly by the upward component of fluid turbulence, (ii) *fluidized sediment flows*, in which the sediment is supported by the upward flow of fluid escaping between the grains as the grains are settled out by gravity, (iii) *grain flows*, in which the sediment is supported by direct grain-to-grain interactions (collisions or close approaches), and (iv) *debris flow*, in which the larger grains are supported by a "matrix"; that is, by a mixture of interstitial fluid and fine sediment, which has a finite yield strength.

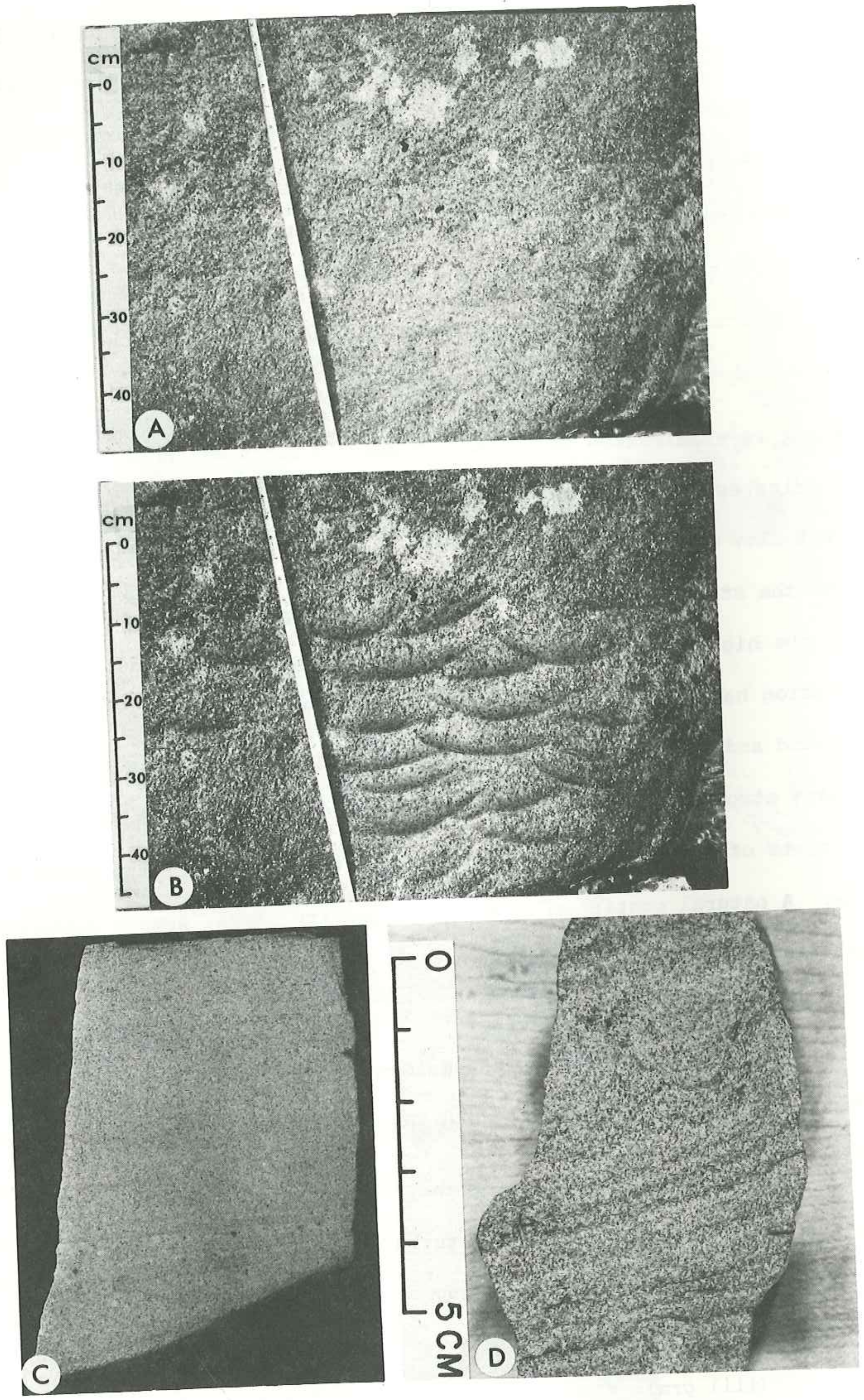


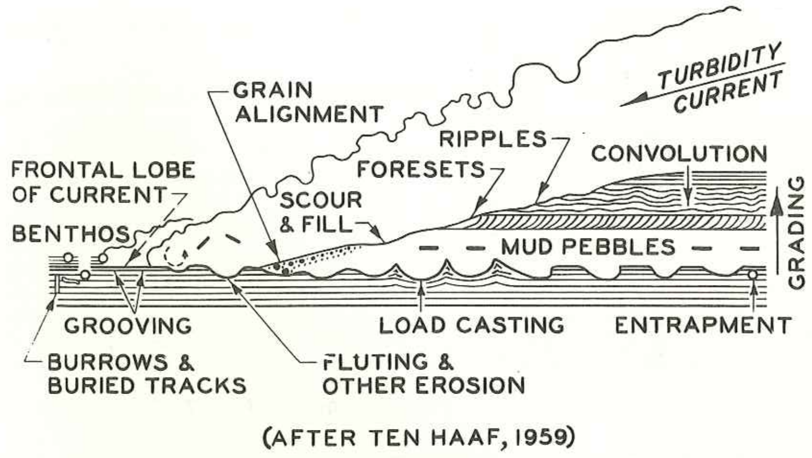
Fig. 54. A, dish structures in a 3 m-thick coarse sandstone bed in the Coulomp River gorge, north of Braux (Excursion day 3); B, same as above, but retouched to emphasize dish structures. C, D, diffuse horizontal and deformed lamination of the type associated with dish structures in massive sandflow deposits.

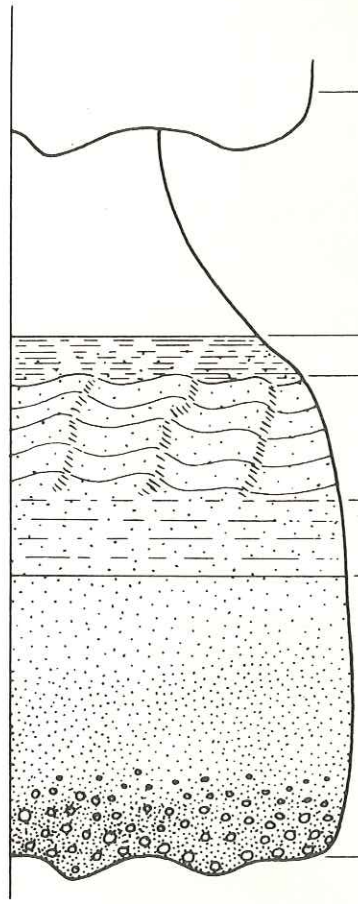
This genetic classification, the hypothetical evolution of a single flow in time and space are depicted in Figure 49; the sequence of sedimentary structures associated with the above-cited subaqueous flow mechanisms are illustrated in Figure 50. It is readily admitted that more than one support mechanism is likely to be involved in any one flow. This hypothetical scheme is tentatively applied to interpret the various sandstone types mapped in the Annot formation.

Debris flow units may include the pebbly mudstone facies (Figs. 20 E, 36 A) and some pebbly sandstones (Figs. 43 C, 51) in which there is poor or no fabric (disorganized pebbly sandstone and conglomerates; cf., Walker and Mutti, 1973). Larger fragments are dispersed at random in a fine-grained matrix (Figs. 42 C, 52). In this type, grains are supported by the strength of the matrix. Pebbles and large fragments of the muddy substrate eroded up-slope (large rip-up clasts) are rafted by cohesive mixtures of sand and some mud in response to gravitational pull on steep slopes. Hampton (1972) suggests that slumps can initiate debris flow. Debris flow deposits and contorted beds are in fact closely associated in certain facies (Figs. 42, 43) which tends to support the contention that slumping triggered debris and other sandflows which are important depositional types in the Annot Sandstone canyon and fan-valley channel Debris flow units are mapped in the Annot, Contes and Menton canyon fill (Figs. 19 A, 20 D) and canyon wall facies (Fig. 31), as well as in some of the proximal base-of-slope deposits including coarse channel deposits in the Lac d'Allos (Figs. 35, 36) and Peïra-Cava area (Fig. 43 C). Debris flows have been best defined on land (an example of this type of deposit in a snow avalanche in the area north of the Lac d'Allos region is illustrated in Fig. 53); they are almost certainly an important factor in sediment transport in submarine canyon axes and relatively steep base-of-slope environments (cf., Figs. 24; 26; lower, 27).

The practical distinction between the fluidized flow (grains supported by the upward intergranular movement of pore fluids) and grain flow (grains bouncing off each other, supported by dispersive pressure) deposits in the field is not clear cut, and I have grouped these under the more general term *sandflow*.

Fig. 55. A, turbidite showing complete sequence of Bouma divisions (see Figs. 56, 57) east of Braux (stop 5, Excursion day 3). Variations of the lower (a) graded Bouma division (B) in sample (Lac d'Allos region, stop 1, Excursion day 4) and (C, D) in core sections (Boucharde drillsite, also in Col de la Cayolle region). Note shale rip-up clast in C.





Grain Size		Bouma (1962) Divisions	Interpretation
Mud	E	Interturbidite (generally shale)	Pelagic sedimentation or fine grained, low density turbidity current deposition
Sand–Silt	D	Upper parallel laminae	? ? ?
	C	Ripples, wavy or convoluted laminae	Lower part of Lower Flow Regime
Sand (to granule at base)	B	Plane parallel laminae	Upper Flow Regime Plane Bed
	A	Massive, graded	? Upper Flow Regime Rapid deposition and Quick bed (?)

Fig. 56. Graded bedding and associated structure in turbidites as related to flow mechanisms (after Ten Haaf, 1959, and Middleton, 1973).

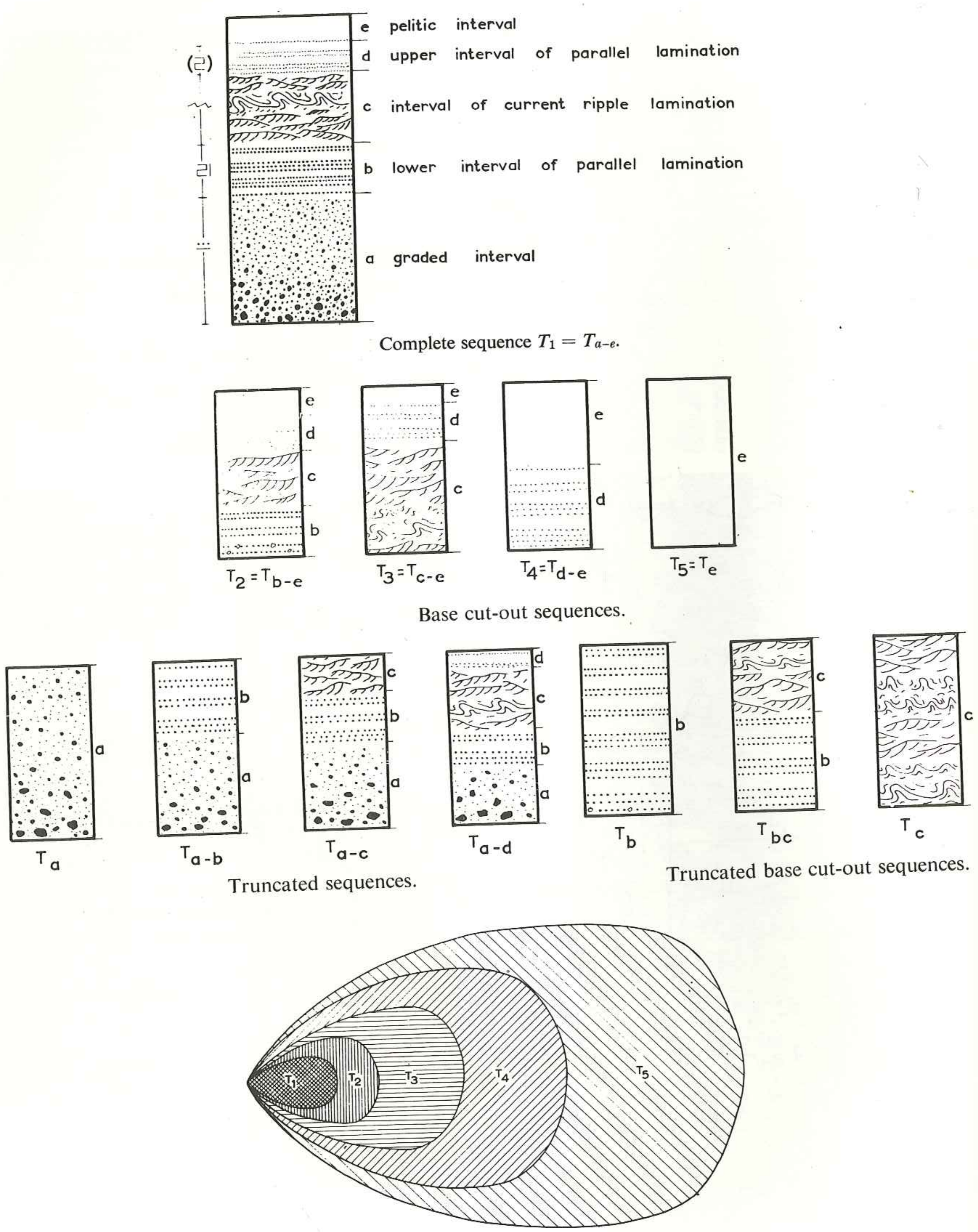


Fig. 57. The upper group of diagrams show examples of theoretically base cut-out and truncated sequences of turbidites. The lower diagram is a hypothetical model depicting the form of a depositional cone showing lateral distribution of above sequence types (after Bouma, 1962).

The sandflow deposits form a majority of the massive (more than 2-3 m thick) sandstones and pebbly sandstones in the Annot Basin. They are particularly characteristic components of the canyon fill facies and fan-valley channel facies.

Features such as dish structures (Fig. 54 A, B) described by Stauffer (1967) and detailed in his study of grain flow deposits are observed in some of the thick, poorly to non-graded (occasionally laminated, Fig. 54 C, D) sandstone strata. Dish structures appear as gentle, concave-up arcs (amplitude: 1-3 cm; length: 5-15 cm). These structures are believed to represent disruption of primary lamination due to the upward loss of trapped water, and load casting of the less viscous upper sand layers beneath in the last stages of movement. It has been suggested (Lopiccolo and Lowe, 1973) that the expelled water first moves within the bed laterally as a result of pre-existing structures; as fluid pressure increases, the fluid is forced to move vertically through the sediment column (Fig. 54 D) thus producing the dishes. Clay and silt, winnowed by the moving water, is deposited at the upper boundary of the zone of the moving water.

The presence of large rip-up clasts (Fig. 20 B) and of denser granules and occasional pebbles floating in a sand matrix associated with dish structures reflects both a high-density, highly fluid emplacement mechanism, and the erosive nature of the sandflows in the Annot formation. Relatively steep slope angles (at least 4.5° to 10.5° according to Middleton, 1970) are required for grain flows; such slopes are not unusual on canyon walls, fan-valley walls and upper (near head) canyon axes. Petrographic and grain size analyses show a low matrix content (in contrast to turbidites) with voids filled with calcareous cement (Fig. 59).

Turbidites, vertically graded deposits (Fig. 55) resulting from low to high density turbulent flow (Fig. 56) have been extensively studied. The vertical and lateral sequence of structures (Figs. 56, 57), defined by Bouma (1962) and based in large part on his study of Peïra-Cava turbidites, is generally accepted.

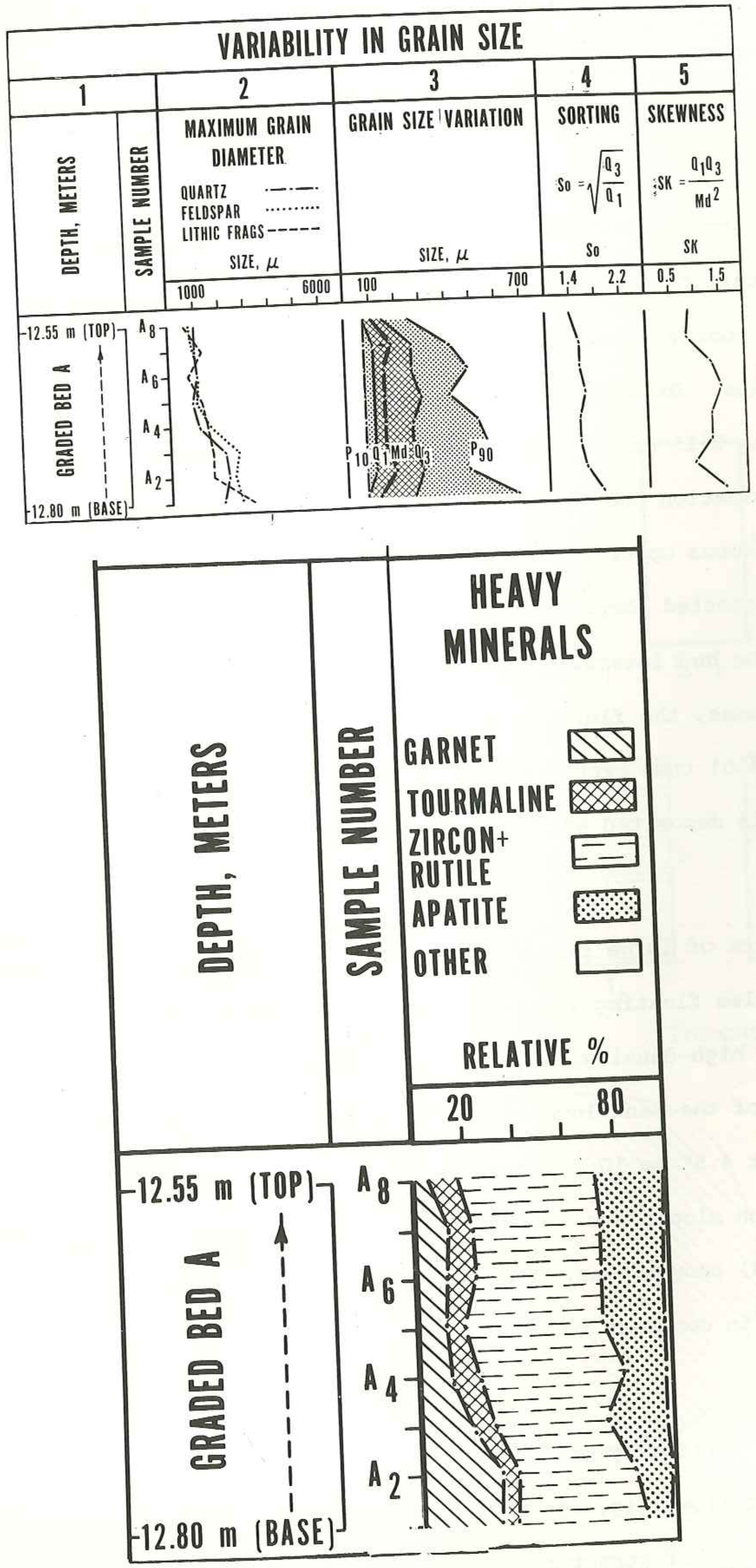


Fig. 58. Vertical, textural and mineralogical variations within a single turbidite (after Stanley, 1961).

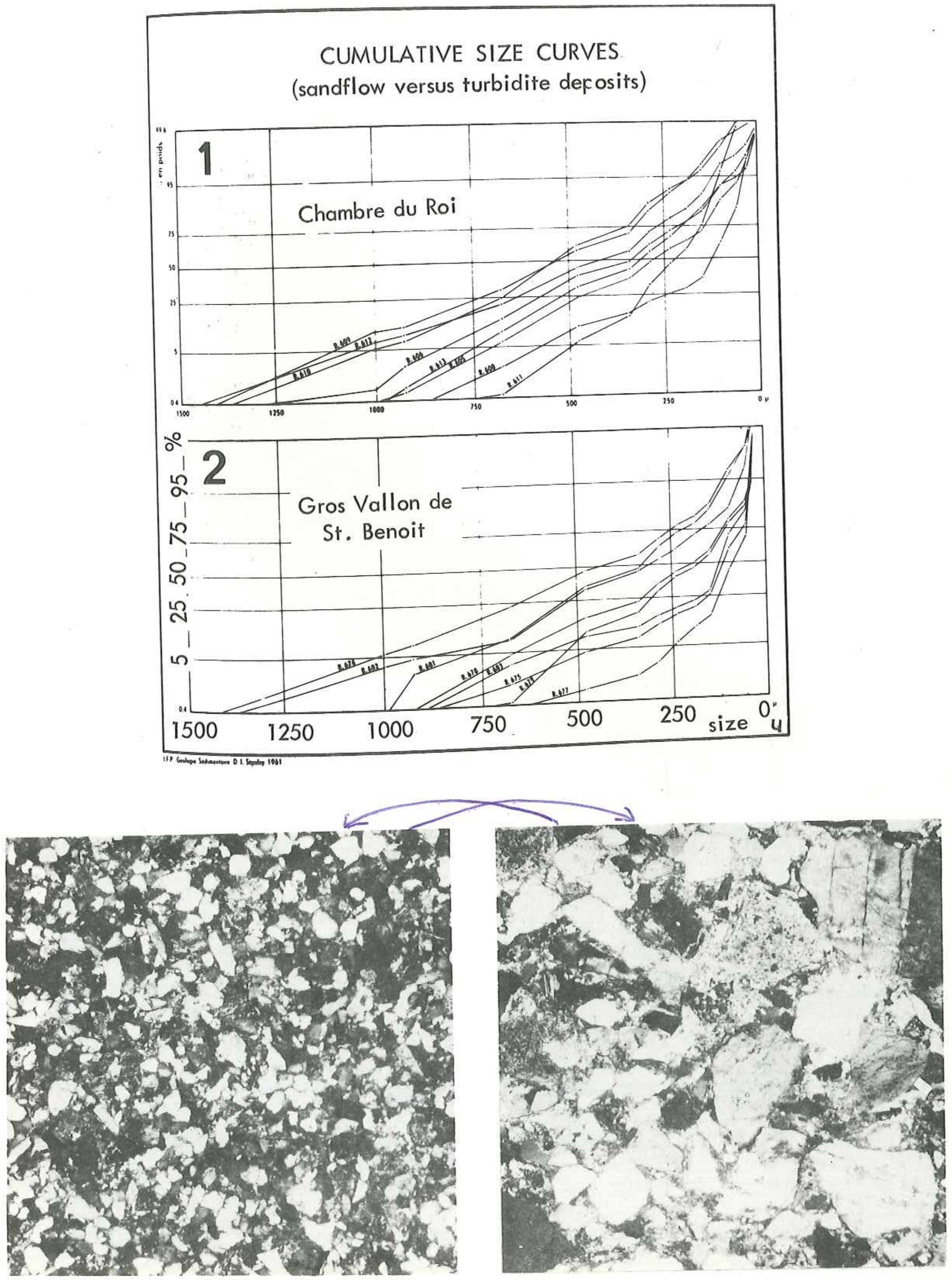


Fig. 59. Comparison of sandflow and turbidite sandstones. Upper, grain size distribution of samples collected on opposite sides of the Coulomp Valley. 1, massive beds from the Chambre du Roi section (stop 8) and 2, turbidites from the Crête du Clot Martin (stop 5, Excursion day 3). Lower left, thin-section of massive sandflow deposit (cement between grains); lower right, section of a matrix-rich sandstone turbidite.

The sandstone turbidites display vertical marked mineralogical as well as textural changes (Figs. 58, 59); petrographic changes in the Annot Sandstone turbidites have been detailed elsewhere (Stanley, 1961, 1963; Bouma, 1962).

The upper (e) turbidite division previously has been attributed a pelagic origin in the Annot Sandstone. Detailed petrographic analyses of such sequences in the ancient rock record (Piper, 1972; Hall and Stanley, 1973) and in cores collected in modern basins (Rupke and Stanley, 1974) show that the so-called pelitic layer sometimes includes vertically graded silt-clay laminae (Fig. 60). These *mud turbidites* represent either the fine tail of turbidity currents or independent fine-grained low density flow deposits.

The finer "structureless" shale sequences between the thin sandstone turbidite sheets on the Annot Basin slope facies and in the fan environments probably have a complex origin which, to date, remains ill-defined. The importance of nepheloid layer and suspension-rich hemipelagic contributions cannot be ruled out, nor can the role of bottom currents which are capable of moving turbid water masses (cf., Heezen and Hollister, 1971). The origin of shales in the Annot Basin requires additional attention.

In summary, the sedimentary structures associated with the sand-rich submarine valley deposits at the Annot, Contes and Menton localities are the end-product of several support mechanisms: grain and fluidized flow, and to a lesser extent, debris flow and turbidity flow. That sandstone turbidites of the same age and composition abound to the north of the massive beds in the Annot, Contes and Menton paleochannels is significant. This indicates, first of all, that the canyon heads and valleys served primarily as temporary through-ways for sands and muds. The submarine valleys were periodically emptied and their fill shifted downslope by various types of sandflow mechanisms as in the case of some modern canyons. That sediment gravity flows probably combined more than one distinct grain support mechanism at different stages of downslope movement is demonstrated in the Peïra-Cava syncline. Here, as in the Col de la Cayolle region there is evidence that slumps are remolded

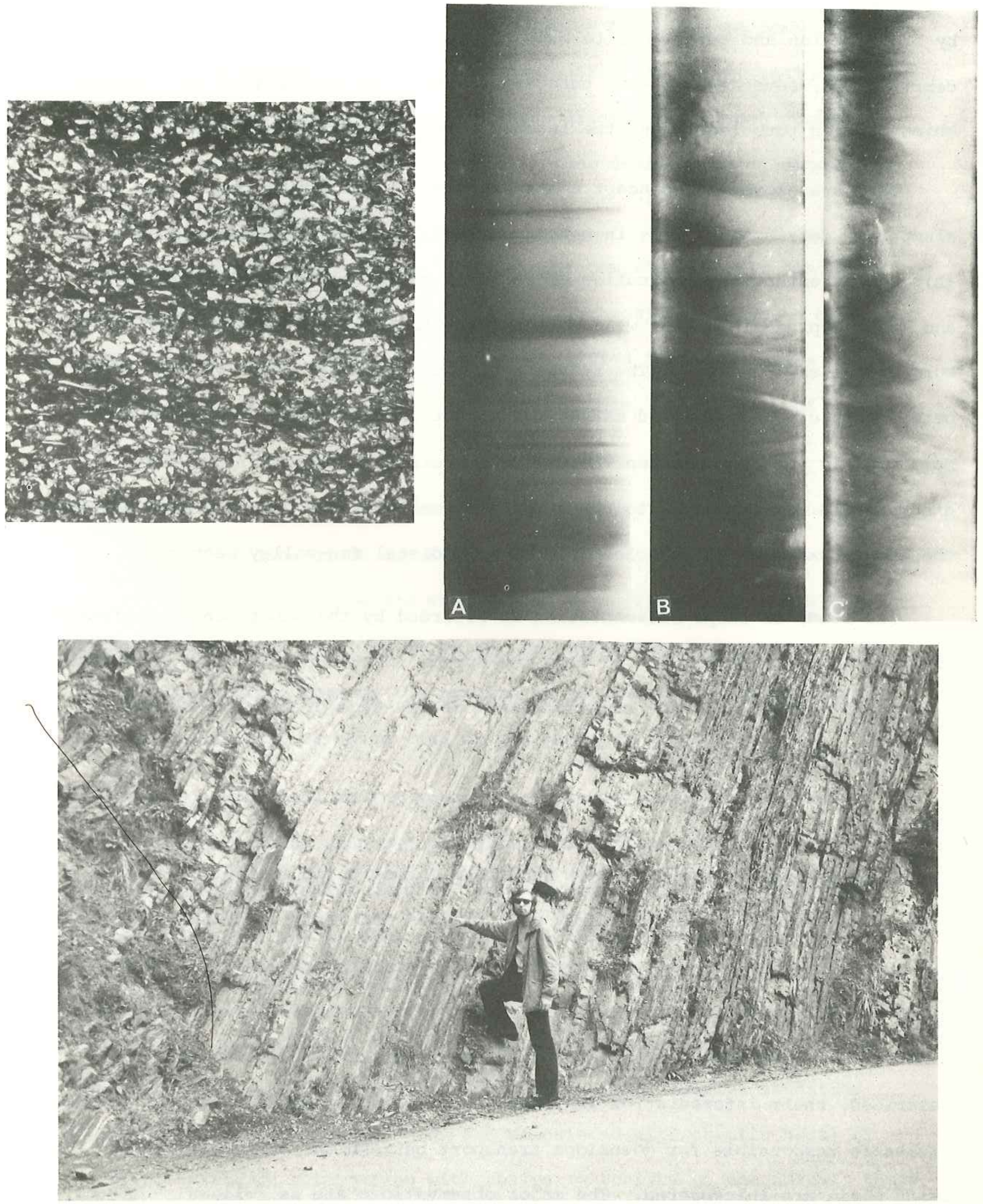


Fig. 60. Upper left, thin-section of pelitic layer showing lamination by silt grains, mica flakes, and plant (dark) matter. Upper right, X-radiographs of core sections from modern mega-fans off eastern North America showing laminated silt and clay (A), burrows (B) and intensely mottled and bioturbated mud (after Kelling and Stanley, in press). Lower, typical pelitic-rich sequence with thin incomplete sandstone turbidites. This Annot Sandstone facies is typical of slope intercanyon and submarine fan interchannel deposits.

by liquefaction and turbulence to high density fluidized flows, grain flows or debris flows; some develop into turbidity currents as a result of acceleration which creates turbulence, and the incorporation of water during downslope flow.

This transformation concept helps explain (1) the higher proportion of slumps and debris flow units in canyon wall and proximal base-of-slope zones, (2) the concentration of sandflow deposits in canyon and fan-valley channels, and (3) the predominance of well-stratified turbidites and mudstones in fan and more distal environments. The sequence of slump to debris flow is best observed between the canyon walls and canyon axis; that of sandflow to turbidite is most clearly apparent between the upper (suprafan) to outerfan; and that of disorganized conglomerates to reverse and normally graded conglomerates between the canyon wall and fill facies and the more distal fan-valley sectors.

The study of slope sedimentation as recorded by the Annot Sandstone facies illustrates the multiplicity of flow mechanisms in submarine valleys, although the actual mechanics of the transformation of one type of flow to another remains poorly defined.

SUMMARY

This examination of the Annot Sandstone Formation at several of the localities where it is particularly well exposed and easily accessible in the French Maritime Alps has as major purpose the detailing of diverse marine slope lithofacies: submarine canyon, intercanyon slope and base-of-slope, including submarine fan sequences. The salient characteristics of each facies are described, their interrelation in space and time is recognized, and the dominant processes responsible for downslope transport between the basin margin and basin plain are interpreted. The major observations are as follows:

1. The sequences (termed type 1 facies) of coarse, massive sandstone and pebbly sandstone strata with only minor intercalations of shale in the regions of Annot, Contes and Menton-Mortola display a finger-like geometry trending essentially in a NNW direction, and are identified as submarine canyon axial and canyon wall facies.

2. A canyon sedimentation model is formulated on the basis of comparison of (a) the three-dimensional configuration of these thick, amalgamated pebbly sandstone and conglomerate (mostly disorganized type) sequences, (b) their paleocurrent patterns and (c) other sedimentary evidence with those of some modern canyons.

3. The canyon axial and near-axial fill facies comprise largely sandflow (grain/fluidized) and debris flow deposits; chaotic slump units are also important, but sequences of well-stratified turbidite-shale alternations (generally termed flysch) form only a minor part of this association.

4. Canyon wall facies are somewhat better stratified, include enhanced proportions of fine-grade deposits and display a diverse suite of strata types: chaotic sandstone and shale deposits of slump and debris flow origin, some thick sandflow deposits, and turbidite-shale cycles. The paleocurrent directions on the margins of the Annot and Contes canyons are generally more variable than in the canyon fill facies.

5. The intercanyon slope facies consist largely of thin, well-defined turbidite sheets and enhanced proportions of shale, some of which is presumably of turbiditic origin. Paleocurrent directions measured in this facies near Annot, Contes and Menton are generally consistent, i.e., trend essentially northward.

6. The typical grès d'Annot flysch facies (type 2) in the Peïra-Cava and the Lac d'Allos-Col de la Cayolle regions includes massive sandstone and pebbly sandstone units (many are associated with chaotic beds) of varying thickness alternating with shales (= schists to the north); these base-of-slope sequences are interpreted in terms of fan models.

7. The massive strata are interpreted as fan-valley channels where sandflow and debris flow mechanisms prevail. Measured changes in the proportion and thicknesses of massive beds and in types of conglomerates (both

organized and disorganized types) provide some indication of the proximality of deposition to the base of the slope. The structures at the base, and within, the massive strata record the importance of erosion associated with channel migration across mud- and silt-rich fan surfaces.

8. Finer sequences at the Peïra-Cava and Lac d'Allos-Col de la Cayolle regions consist largely of moderate to thin turbidite sheets and shale; these units, interbedded between the more massive sandstone, are interpreted as intervalley fan deposits, and include overbank and possibly levee deposits. Paleocurrents record radially oriented trends comparable to dispersal patterns in modern fan lobes.

9. The lateral increase in proportion of shale and thinner, better stratified sandstone sheets denotes the lateral transition from mid- to outer-fan environments; vertical variations in the proportion of sandstone to shale records changes in relation to channel distributary patterns and the configuration of lobes formed during the deposition of the fan.

10. Shales probably record hemipelagic as well as turbiditic processes, but their origin at this time remains undefined.

11. Regional mapping of the facies described above serves to define the physiography of Annot Basin in uppermost Eocene to lowermost Oligocene time and helps to determine the zone of transition from slope to base-of-slope environments. The paleobathymetry of the slope environments is interpreted on trace fossil (including the *Nereites* assemblage) and sedimentological evidence; infraneritic to bathyal depths are postulated.

12. The excellent quality of Annot Sandstone exposures, trending parallel or subparallel to the paleoslope, enables sedimentation units to be traced from intermediate to deep water environments along the major paleocurrent dispersal paths. This formation is thus uniquely disposed for an evaluation of downslope transport mechanisms (i.e., slump, sandflow, and debris and turbidity current flow). Although the mechanics of the transformation

from one type of flow to another remains undefined, the paleochannel system affords a rare opportunity to examine the possible continuum from slumping to turbidity current flow.

In summary, the Annot Sandstone facies examined here can serve as a type example of the submarine canyon — fan-valley continuum.

ACKNOWLEDGMENTS

My appreciation is expressed to Mr. J. A. Wexler, University of Puget Sound, for providing as yet unpublished trace fossil and paleobathymetry data, and to Drs. J. P. Bertrand, Institut Français du Pétrole, R. F. Dill, U. S. Department of the Interior, and G. V. Middleton, McMaster University, for furnishing illustrations. Other authors and publishers also are thanked for granting permission to reproduce published illustrations in this guide. Technical assistance has been given by Messrs. L. Isham, H. Sheng, and S. Waitzman, and Ms. D. Copeland and Mrs. D. J. Stanley, all of the Smithsonian Institution. Financial support used in the preparation of this study, part of an on-going study of the Annot Sandstone, was made available by Smithsonian Research Foundation grant 450137.

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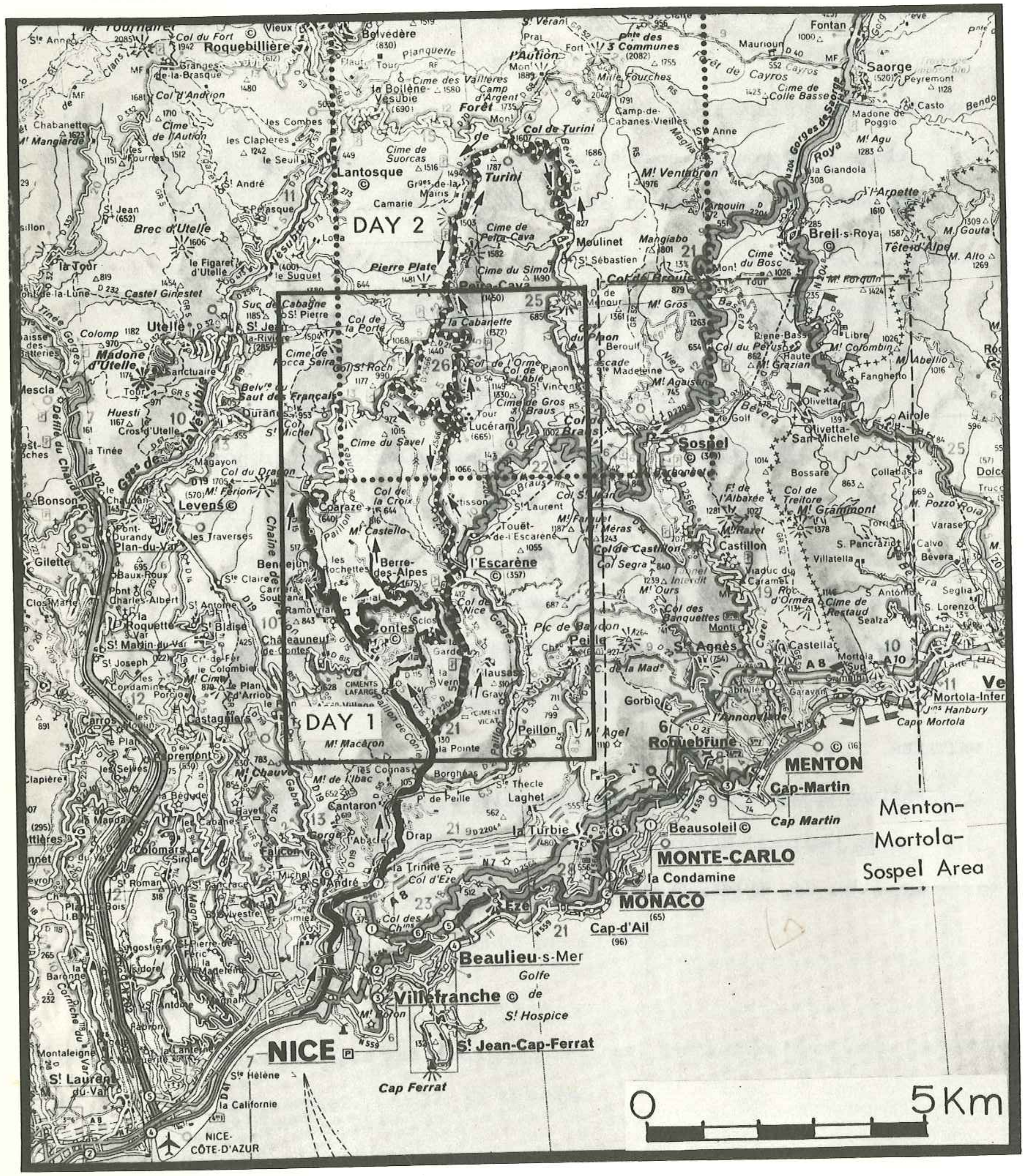

Fig. 61. Map showing suggested itinerary for Excursion days 1 and 2 (after Carte Michelin 84). Enclosed areas refer to geological maps in Figs. 11, 12 and 13.

APPENDIX

A FOUR DAY ITINERARY FROM NICE TO STUDY ANNOT SANDSTONE SUBMARINE CANYON AND SLOPE FACIES IN THE FRENCH MARITIME ALPS

DAY 1. *CONTES-COARAZE REGION NORTH OF NICE*

PURPOSE: To examine submarine canyon (axis, wall) and adjacent slope facies of the Annot Sandstone *s.l.* Formation (= grès de Contes) in the region just north of Nice.

0 km — Starting at Nice, proceed northward on route D2204 (sign Sospel) following the Paillon River.

11 km — Turn left at La Pointe de Contes onto route D15 (2.5 km from Contes) and head northwest along the Paillon de Contes River.

13.5 km — Pass the La Farge cement works and take a small route, D115, to the right.

Stop 1. A general reconnaissance of the complete lower Tertiary sequence, or "trilogie nummultitique", can be made from this locality at the southern end of the Contes syncline. From here one can observe the Eocene limestone, or *Calcaire nummulitique*, exposed along the road at this point, the blue shales, or *Marnes bleues*, and friable *grès de Contes* (a lateral equivalent of the Annot Sandstone Formation). The latter is observed underlying the small perched town of Contes and forms the hills above to the northeast. Follow the small road (sign La Vernea de Contes, Sclos de Contes) northeastward to eastern side of Contes syncline. This small road climbs across the complete Marnes bleues section.

15.5 km — Turn left, following sign Sclos de Contes.

16.1 km to 16.5 km — *Stop 2.* Good exposures of canyon wall facies at the base of the Annot Sandstone Formation crop out along the road. Note the importance of slump deposits between, and within, very thick friable sandstone units (some of these amalgamated units are

10 to 15 m thick). These include sand flow (grain/fluidized flow) deposits. Coarse sand and granule size material predominate. Thick units are sharp-based, poorly to moderately graded vertically, and display generally poorly-developed sole markings. The rhyolite, andesite, and small red granite pebbles are believed to have a "southern" origin, i.e., from a once-emerged Esterel-Corsica source area. The abundance of plant fragments indicates initial transport of continental sediment by rivers to the coast (perhaps a deltaic environment) prior to redeposition and rapid burial in the marine environment. Some thin, graded b-c-d turbidites showing distinct horizontal and wavy lamination are preserved between the thick massive beds. These finer-grade units may represent the more normal slope sedimentation between the down-canyon wall sand flows and slumps. Material appears to have been transported along a north dipping slope; the originally stratified sand and mud deposits failed and were entrained downslope in a northwesterly direction along the east wall of the major submarine valley.

20.2 km *Stop 3*. A thick (about 4 m), sharp-based, massive coarse-textured sandstone unit displays possible dish structures along a weathered face. Note shale clasts and the poor development of sole markings at the base of this sand flow bed which lies above thin turbidites. The road, trending to the north, follows a classic flysch sequence consisting of thin, well-stratified sandstone turbidites alternating with shales; some of the latter may be mud turbidites while other fine-grained units are hemipelagic in origin.

21.0 km *Stop 4*. Slope facies on the eastern margin of the Contes submarine canyon comprise well-stratified sandstone (20 to 200 cm thick) and shale units. Most turbidites are laminated from base up

(b-c-d-e; c-d-e units) and may also display well-developed convolute lamination. Sole marks show predominant transport directions to the NNW. As one progresses northward, the road cuts back down section, i.e., back into the Marnes bleues, and meets route D215. Turn left (3.3 km from Berre-les-Alpes) and begin climbing in a westward direction.

21.6 km The road climbs in sinuous fashion back up the stratigraphic section and cuts into a sandstone-rich flysch facies at the base of the grès de Contes.

23.0 km Note a good example of a contorted slump interbedded in a massive sandstone; this sequence (as at Stop 2) is interpreted as a probable canyon wall deposit.

23.7 km At the road junction make a right turn on D215 (1 km from Berre-les-Alpes). Note the sandy flysch (slope) facies as one approaches the village of Berre-les-Alpes (682 m). This village is perched on coarse sandstone units.

24.5 km to 25.2 km *Stop 5*. Examine the coarse-textured sandflow units (grain/fluidized flow, and possible debris flow) along the road just beneath village of Berre-les-Alpes. Some are clearly lenticular and channelized, and several units contain gravel and, locally, large reworked sandstone blocks. Proceed to the village center where an excellent panorama of the Paillon de Contes and of the town of Contes below is available. Proceed northward, following a small paved road heading NNW toward the Coste Nègre and Mont Castel.

26.0 km Take the right branch at a fork in the road.

27.5 km Follow the road to the end, and then walk along the large trail (less than a kilometer) to the Mont Castel (elevation 816 m).

Stop 6. The thick amalgamated sandstone sequence forming this promentory is interpreted as a submarine valley fill. The thick sand flow (fluidized grain flow) units include pebbles to 1 cm in diameter. Note, once again, the red grainte and rhyolite of Esterel-Corsica origin. This site affords an excellent view of Coaraze, some two kilometers to the northwest as well as an excellent panorama of the peaks and valleys at the northern end of the Contes syncline.

Possible lunch stop.

29.8 km Return SSE to Berre-les-Alpes.

31.3 km At a road junction, make a right turn on D615, on the road leading to Contes (7 km), i.e., heading west. Here the road tends to follow the general structural surface of the westward dipping sandstones strata.

31.8 km *Stop 7.* Sand flow (fluidized/grain) units in this sector show a sharp base and some graded bedding. One massive sandstone displays vague dish structures; it lies above a 1.5 km thick finer-grade well-stratified flysch section.

33.4 km to 33.7 km *Stop 8.* Good examples of amalgamated massive sandstone units and coarser debris flow deposits. The wedge-shaped configuration of the sand flow strata indicates channelization. Pebbly (including crystalline pebbles about 1 cm in diameter) sandstone, large spheroids, and plant- and lignite-rich layers are observed. Walk along the road to the junction where the road from Castellar enters route D615.

37 km Large spheroids in exposures on the left of the road (about 0.4 km from Contes) have been broken by blasting during construction of the road.

38 km Upon reaching the main road, D15, turn right (to the NNW) and

proceed toward Bendéjun. This section of road follows the very thick sandstones along the Paillon de Contes. This is a good area to observe submarine valley fill deposits.

38.8 km *Stop 9.* The gorge cut by the Paillon de Contes consists of massive, coarse-grade sandstones, among the thickest sand flow units observed in the Contes syncline. This sequence includes pebbly sandstone (debris flow) units with large mud clasts and crystalline pebbles exceeding 1 cm in diameter distributed through the sandstone. Both disorganized and organized conglomerates are observed. The road eventually crosses the Paillon de Contes and begins to climb toward Bendéjun.

42.4 km *Stop 10.* Massive 5 to 6 m thick submarine valley fill deposits are well-exposed in a small quarry (sign Bendéjun Supérieur). The sandstones here are somewhat better sorted and less coarse-textured than those exposed along Paillon de Contes observed earlier.

45 km *Stop 11.* The base of the grès de Contes section lying just above the steeply dipping Marnes bleues at this locality consists of a coarse-textured sandstone unit (7 m). Close inspection reveals slumped units, possibly deformed grain flow and turbidite units, and is similar to the units observed at Stop 2. This sequence probably denotes the western canyon wall facies. This stop affords a good view of the Mont Castel section to east, and the village of Coaraze 2 km to north.

47 km *Stop 12.* Coaraze (620 m) is an attractive and as yet unspoiled XIIth century village built on SSE dipping sandstones. Sole markings on strata at the base of the village show current directions oriented toward the north. A visit, well worthwhile, reveals dwellings built of sandstone and older limestone. An

excellent view of the surrounding terrain is to be had from the church square (XIVth century). Note in particular the wooded peak called Cime du Savel about 3 km northeast of Coaraze. This exposure, formed by a sandy flysch sequence consisting of thick sandstones (turbidites and sand flow units) and shales, is interpreted as a base-of-slope upper fan sequence; it occupies a position in the paleobasin between Contes and Peïra-Cava (sandstone sequences in this syncline are examined on Day 2).

70 km Return to Nice by way of routes D15 and D2204.

DAY 2. *COL DE L'ORME-PEIRA-CAVA-COL DE TURINI-COL ST. ROCH*

PURPOSE: To examine slope and submarine fan facies of the Annot Sandstone *s.l.* Formation (= grès de Peïra-Cava) north of Nice.

0 km Starting at Nice, follow route D2204 (sign Sospel) northward along the Paillon River.

11 km At La Pointe de Contes, turn right staying on D2204.

21 km At l'Escarène, follow route D2566 northward.

27.5 km At Lucéram, take route D21 and continue northward toward the Col de l'Orme (1000 m) and Baisse de la Cabanette.

32.5 km Routes D21 and D54 meet; stay on D21. Climb across the Calcaire nummulitique and Marnes bleues.

33.5 km to 36 km *Stop 1.* Upper submarine fan (suprafan) sequence above the Marnes bleues. A good view of the sandy flysch sequence forming the Cime de Rocaillon (1440 m) can be had west of road. The stratigraphic section of the grès de Peïra-Cava begins with a fine flysch sequence composed of b-c-d-e and c-d-e turbidite sands and muds above the Marnes bleues. The first major sandstone is "dirty", includes abundant mica and plant matter and trace fossils (worm tubes), and displays horizontal lamination. The subsequent sequence comprises classic turbidites with excellent sole markings, as well as thick sand flow (fluidized/grain and debris flow) and chaotic slump units. Many units are of a composite nature: they display chaotic and/or coarse debris flow structures at their base and trend upward as graded and laminated sandstone turbidites. Organized conglomerates are considerably more important here than at Contes. There is ample evidence of erosion: large deformed shale clasts, marked eroded base of beds, etc. Some of the thicker sand flow (grain/fluidized flow) units are interpreted as proximal migrating fan valley sequences. These are interbedded with finer-grained alternating sandstone turbidites and shales, possible mud turbidites and hemipelagic units, representing intervalley overbank deposits. The structures of some of these sequences at this locality have been illustrated by Bouma (1962) and Lanteaume et al. (1967). The paleocurrent directions are oriented, for the most part, toward the north. Walk for several kilometers observing the excellent sections exposed along the road, and then proceed to the Baisse de la Cabanette.

37.7 km Baisse de la Cabanette (1372 m) designated the junction of routes D21 and D2566 about 2.5 km south of Peïra-Cava; turn right onto D2566.

40.1 km Peïra-Cava (1581 m). Suggested lunch stop. Continue north on D2566 toward the Col de Turini. The thick sections of sandy flysch forming the western sector of the Peïra-Cava syncline can be observed from a distance.

47.1 km At the Col de Turini (1607 m) follow route D2566 to the east and then south toward the town of Moulinet. The road descends the stratigraphic section and traverses the Tertiary section. Proceed to the Calcaire nummulitique. Tunnel.

56.1 km After reaching the Calcaire nummulitique double back on this same road and climb back across the Marnes bleues (= *schistes*) to the base of the sandstone formation.

57 km to 59 km *Stop 2.* The grès de Peïra-Cava at this locality appear somewhat more distal than the facies observed earlier at Stop 1. The section includes good examples of mid- to outer-fan deposits. The base of the section consists of dark flysch of possible outer fan and/or interchannel origin and includes distinct b-c-d turbidites. The section is well-stratified and comprises a somewhat lower proportion of very thick sandstone units and

disorganized conglomerates than at Stop 1, but an enhanced series of fine-textured and more complete turbidite-shale sequences. The thick massive sand flow (grain/fluidized and debris flow) units are interpreted as migrating fan valley deposits. These display evidence of turbulent flow and erosion (sharp base of strata, large shale clasts, etc.). The paleocurrent directions at this locality, mapped by Bouma (1962), trend E-W and NW-SE at the base of the section and northward in the upper part of the section. Proceed up section toward the Col de Turini.

64.5 km At the Col de Turini (altitude 1607 m) there are several optional stops. A 10 km stretch of road (D70) from the Col west to La Bollène-Vésubie crosses the western part of the Peïra-Cava syncline and reveals suprafan to outer fan facies essentially similar to those observed at Stop 2 between the Col de Turini and Moulinet. A much smaller route (D68) north of the Col to l'Aution-Pointe des 3 Communes reveals enhanced proportions of thinner and somewhat finer-grade sandstone units. This more distal facies may represent the outer fan to basin facies (largely broad thin flows and less channeling). Return south on route D2566 past Peïra-Cava.

74 km Pass the Baisse de la Cabanette, and proceed southward on D2566 toward Col St. Roch at the southern end of the Peïra-Cava syncline.

75.2 km to 76.1 km *Stop 3.* A good sequence of proximal upper fan units are exposed at the first sharp turn along the road. Observe thick sand flow (debris/fluidized flow) units and some evidence of slumping. Many of the sandstones display abundant trace fossils and burrows. These units were deposited near the base-of-slope, probably at depths exceeding those at which the sequences to the south at Contes-Coaraze and Cime du Savel accumulated (bathyal according trace fossil assemblages).

77.1 km *Stop 4.* The massive sand flow (grain/fluidized) sandstones at this locality are rich in plant matter; as at Contes, this indicates the importance of terrestrial input and rapid burial. Note the large convolutions and soft-sediment deformation within the sandstone and the erosional base of the strata.

77.7 km to 77.8 km *Stop 5.* A remarkable exposure of a large chaotic sandstone-shale (about 5 m thick) deposit is observed along the road cut. The slumped mass is covered by about 20 m of massive amalgamated sandstones and probably represents a proximal upper fan valley deposit localized near the base of the slope. These deposits lie above the Marnes bleues which form the Col St. Roch.

79 km At the Col St. Roch (990 m) follow route D2566 toward Lucéram.

85 km At Lucéram, proceed southward on route D2566 toward l'Escarène, and continue to Nice on D2204.

112.5 km Return to Nice.

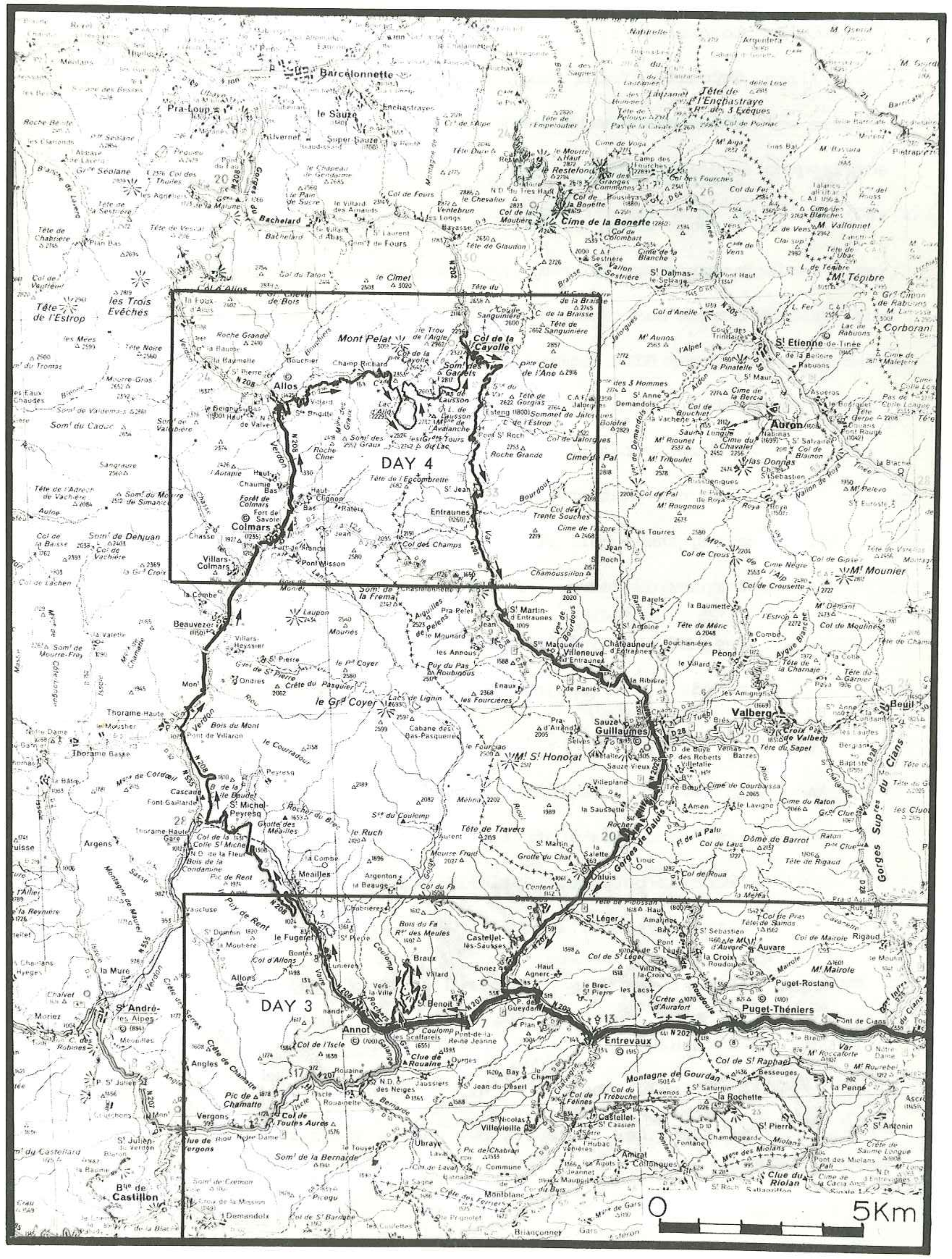

Fig. 62. Map showing suggested itinerary for Excursion days 3 and 4 (after Carte Michelin 81). Enclosed areas refer to geological maps in Figs. 9 and 10.

DAY 3. *NICE-ANNOT-COL D'ALLOS REGION*

PURPOSE: To examine submarine canyon (axis, wall) and adjacent slope deposits of the Annot Sandstone Formation at its type locality, and compare with facies observed at the Contes locality (Day 1).

0 km — Starting at Nice, follow the Promenade des Anglais to the airport which is built on a gravel-rich delta of the Var, the major river flowing into the Mediterranean in this part of the French Maritime Alps. Follow the sign to Digne and proceed on highway N202 which follows the Var northward. Note the present activities modifying the river including revetment and stabilization of the river banks and extensive dredging. Note also the Quaternary alluvial gravel deposits locally exposed along the road. This route from Nice to Annot traverses a thick complex of Mesozoic and Tertiary calcareous and shale formations.

38 km — West of the Tinée River, the Var suddenly changes course and trends E-W following the major structural trend of the region (Arc de Castellane).

72 km — Entrevaux, a fortified town designed by Vauban, occupied for many centuries a strategic position on the Var and served as a frontier outpost. Optional coffee (Pastis) break at this attractive locality.

78 km — At Pont de Gueydan, proceed westward toward Annot on route N207.

85 km — Route N207 makes a sharp left turn (south) in the hamlet of Les Scaffarels; another main road (D908) continues directly to Annot. Take neither of these, but make a sharp right turn (heading north) onto the small narrow road next to hotel in Les Scaffarels.

85.4 km — *Stop 1.* Climb along southern end of Annot syncline, passing just below the massive sandstone cliffs lying above the Marnes bleues Formation. At this locality observe large broken blocks

of friable Annot Sandstone lying on right side of road which show details not readily noted in weathered outcrops: stratification, mudstone clasts, plant fragments, small pebbles including red granite and rhyolite of Esterel-Corsica origin. The sandstone has a feldspathic, lithic micaceous composition. Note the lithologic similarities with the grès de Contes (Day 1).

85.9 km to 86 km — *Stop 2.* As one enters the narrow valley of the Coulomp River, the cliffs of thick amalgamated sandstone strata dominate the valley on the left (west) in marked contrast to the much better stratified sandstone-shale flysch sequence forming the hills east of Coulomp River. The complete Tertiary sequence above the well-stratified Upper Cretaceous limestones and marls comes into view as one walks downhill, northward, along the small road: Calcaire nummulitique, Marnes bleues and grès d'Annot formations.

86.5 km — Cross the small bridge over the Coulomp River and proceed along the new road (D110) to Braux.

88.9 km — *Stop 3.* This point along the road affords an excellent view of the well-stratified sandstone-shale flysch sequences straight ahead (to the north) which form the Crête de la Barre and Crête du Clot Martin, and the thick amalgamated sandstone units (some >30 m thick) west of the Coulomp River.

90.6 km — *Stop 4.* Examine the flysch facies forming the southern end of the Crête de la Barre. This complex includes classic turbidites (some of which display the complete Bouma sequence), a few thick sand flow (grain/fluidized flow) and chaotic slump beds. The sequence is interpreted as a canyon wall facies (compare with Stop 2 on Day 1). Some anomalous current directions (ESE) probably reflect transport along lateral tributary valleys into main N-S trending canyon axis which lies about 1 km to the west.

90.0 km *Stop 5.* At the sharp turn in road, take a steep small dirt road to the cabin on the Crête de la Barre (about 0.9 km), and walk about 1 to 2 kilometers NNW on the trail which follows the Crête toward the torrent (Ravin du Gros Vallon). This trail crosses excellent exposures of sandstone turbidites and sand flow (grain/fluidized and debris flow) deposits. A few chaotic (slump) units are also noted. Sole markings show transport toward the NW and NNW as one proceeds northward and approaches the torrent. Trace fossils are particularly abundant and varied. This sequence is interpreted as a slope (intervalley) facies. Return to the main road and proceed northward to Braux.

92.4 km *Stop 6.* Stop to look at thick sandstone cliffs across the Coulomp valley. Note irregular stratification due, in part, to massive slumping and channelized sand flow; there is some indication of transport toward the west, i.e., toward the canyon axis. Also note the very sharp erosional surface at the base of the sandstone formation; one can observe where the sands originally truncated and actually cut into the underlying Marnes bleues.

92.9 km At the village of Braux, return south.

93.2 km Make a right turn on the older (and lower) road from Braux to Les Scaffarels, and again note the large sandstone cliffs west of the Coulomp River.

95.8 km Make a right turn on the main road (D110) to Les Scaffarels.

96.7 km Cross the small bridge over the Coulomp River and make a left turn on the road which parallels the Coulomp.

97.0 km *Stop 7.* Observe the marked unconformable surface between the basal Calcaire nummulitique and underlying stratified sequence of Upper Cretaceous limestones and marls.

97.7 km Pass under small railroad bridge.

97.9 km Make a right turn on the main highway N207 (3 km from Annot).

98.4 km At Les Scaffarels, follow route D908 to Annot-Col d'Allos. The Vaïre River lies west of the road.

100.6 km The town of Annot is famous for "ces grès, sa vieille ville". Its old center dates from the Middle Ages and the Renaissance. Suggested lunch stop.

Stop 8. The purpose of this stop is to examine exposures of the Annot Sandstone Formation at its type locality. Proceed to the southern end of the Annot railroad station, and follow the signs which denote the trail to the Chambre du Roi. This excursion allows a good, first-hand examination of massive channelized sand flow (grain/fluidized flow and some debris flow) deposits interpreted as a submarine canyon fill (Stanley, 1961, 1974). These units include coarse-grade sandstone and pebbly sandstone; crystalline pebbles to several centimeters in diameter are noted. These are sometimes concentrated at the base of beds (organized pebbly sandstone), but are more commonly distributed throughout the sandstone units (disorganized pebbly sandstone). Large shale clasts, poor sole markings, and sharp-based amalgamated sandstone units predominate. A section of thin turbidites intercalated between the massive sandstones is observed along the trail just beyond the Chambre du Roi. This thin flysch section displays an excellent assemblage of trace fossils (including bathyal depth *Nereites* assemblage) and sole markings indicating a northward paleocurrent direction. Follow the trail to the top of the formation. From here one can observe the gorge of the Galange River to the south, and the Coulomp valley, Braux and St. Benoit to the east. Take the trail northward to Les Portettes (a natural sandstone bridge produced by weathering and erosion of the friable sandstone) and continue northward. The trail will eventually lead toward the Beite valley and back down to Annot, passing the Chapelle Notre Dame-de-Vers-la-Ville, which dates from the time of Jeanne de Provence. Allow about three hours for this excursion. After returning to Annot, proceed northward on D908. Exposures along this road toward Le Fugeret are generally poor and follow the structural surface of the Annot Sandstone.

106 km Le Fugeret.

108.8 km Note the village of Méailles in the distance to the east which was built on the Calcaire nummulitique. Le Ruch (altitude 2100 m), the peak above Méaille, comprises a well-stratified sequence of thick consolidated sandstone turbidites unlike those observed at Annot. This sequence is similar to that at the Cime du Savel north of Contes (Day 1), and is interpreted as a base-of-slope deposit consisting of proximal suprafan facies.

118.7 km St. Michel-Peyresq (1431 m).

126.7 km Make a right turn at the junction of routes D955 and D908; stay on D908 and proceed northward.

127.5 km Cross the Verdon River and make a right turn, staying on route D908 which parallels the Verdon.

132.9 km Beauvezer (1150 m) or Colmars (1259 m), an interesting fortified town, at 139.4 km will be selected as a stop at the end of Day 3.

DAY 4. *ALLOS-LAC D'ALLOS-COL DE LA CAYOLLE*

PURPOSE: To examine the typical sandy flysch facies of the Annot Sandstone, including base-of-slope and fan deposits in the Lac d'Allos-Col de la Cayolle region, and compare with facies observed at the Peïra-Cava locality (Day 2).

0 km Proceed northward to the village of Allos about 10 km from the Col d'Allos (2240 m). Make a right turn onto the small road (D226) south of village toward the Lac d'Allos and climb past Villard and Champ-Richard. The road is narrow and extremely steep (15°).

13 km *Stop 1.* Park the vehicle near the Cabane du Laus (>2100 m) north of the Lac d'Allos, and plan on being picked up at Col de la Cayolle (i.e., vehicle must go back to Allos and then proceed by way of the Col d'Allos, Barcellonette and the Col de la Cayolle, a distance of about 73 km). Climb to the refuge at the northern end of the Lac d'Allos (2229 m). As one walks around the lake (little more than 2 km), observe the small deltas forming at foot of mountain torrents at the northeastern and southern ends of the lake. The Annot Sandstone Formation, consisting of coarse sand flow (some submarine fan valley) units and schists (overbank deposits), forms the Tours du Lac (peaks of the southern and southeastern margin of the lake). The sequence displays both suprafan and outer fan (fine flysch) facies, not unlike those observed at Peïra-Cava (excursion Day 2). The tallest peak north of the lake is the Mont Pelat (3052 m) consisting of structurally deformed Upper Cretaceous and Eocene allochthonous sequences, mostly flysch. The peaks along the northern and northwestern end of the lake include Eocene (Priabonian) sandstones (some of them similar to grès d'Annot) of the Subbriançonnais nappe (cf., Mont Monier). The Tête de

Valplane southwest of the lake comprises Eocene (Lutetian) conglomerates of the Subbriançonnais nappe. After examining the Annot Sandstone of the Tours du Lac proceed along the major trail to the northeast. At a certain point two possible trails may be taken: (1) via Lac d'Allos-Pas de Lausson (2603 m) - Col de la Cayolle (2376 m), a distance of about 8 km; or (2) Lac d'Allos-base of the Mont Pelat (and possible climb to top of the Mont Pelat which requires an extra 2 hours of hard climbing to its summit) - Lac de la Petite Cayolle - Col de la Petite Cayolle (2642 m) - Refuge du Col de la Cayolle (a distance of about 6 km). Both trails offer excellent views of the Lac d'Allos and surrounding peaks. The view to the east from the Pas de Lausson reveals a series of crests (from south to north: Roche Grande, Tête de Gorgias, Cime de Cartairet, Pointe Gias Vieux, Tête de Sanguinière and Col de la Cayolle) all formed of well-stratified base-of-slope units of the grès d'Annot (>600 m thick). The thicker sandstone bodies are interpreted as proximal fan valley facies and include some sand flow (grain/fluidized and debris flow) deposits as well as turbidites (Stanley, 1963); thinner more flysch-like sequences represent intervalley or more distal turbiditic overbank and hemipelagic deposits. A regional examination of the sole markings indicate a westward dipping paleoslope, i.e., from the northern end of the Argentera-Mercantour Massif. The presence of some thick pebbly mudstone deposits and some chaotic bedding indicates downslope failure on gradients probably exceeding 3°. The composition of pebbles and of the sandstone suggests a provenance from the erosion of the Permian-Triassic clastic sequences (now for the most part eroded) of the northern Argentera Massif (Stanley, 1961, 1965).

86 km Proceed to the Col de la Cayolle, route D202.

87 km to 88 km *Stop 2.* Good exposures of Annot Sandstone proximal base-of-slope or suprafan facies are observed along the first 2 kilometers of hair-pin turns on the southern flank of the Col de la Cayolle. In addition to turbidites and thick sand flow deposits, one can observe thick debris flow units, consisting of pebbly sandstone and coarse muddy sandstone, as well as several chaotic (slump) units. One particularly interesting deposit includes a 2 m thick concentration of large (>5 cm) shale clasts within a massive (>10 m) sand flow (grain/fluidized) unit. The base of some thick sandstones include granules and small (1 cm diameter) crystalline pebbles (organized conglomerates); the base of these thick sandstones cut underlying finer grade series. A tunnel is cut through the grès d'Annot further south. Note that most of the peaks each of the road are formed of Annot Sandstone fan sequences (>600 m). Continue southward on D202 passing a sign indicating the source of the Var River above the village of Esteng. Follow the Var past Entraunes.

120 km Town of Guillaumes.

121 km At the Pont des Roberts bridge which crosses the Var, note the white, cross-stratified quartzose sandstones which are the typical clastic facies of Werfenian (Lower Triassic) age. These sandstones lie unconformably above the thick sequence of red and green Permian shales which form the Dôme de Barrot. These red beds, incised by the Var River, form the spectacular Gorges de Daluis. The road winds its way through the red bed sequence for a distance of 9 kilometers.

131.5 km Village of Daluis.

141 km Pont de Gueydan (water gap formed by the Var cutting across steeply dipping limestones). Turn east onto route N202 and follow the Var past Entrevaux and Puget-Théniers back to Nice.

219 km Return to Nice.